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ANNUAL REPORT: LONG-TERM MONITORING AND DATABASE DEVELOPMENT FOR APPLIED ANAEROBIC DIGESTION TECHNOLOGY IN CANADA

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PREFACE

This annual report is intended to summarize the activities of the Canadian Applied Anaerobic Digestion Technology Database and Computer Conferencing System and Anaerobic Digestion System Monitoring Program for 1986. A discussion on current and future trends in anaerobic digestion technology in Canada, the United States and Europe is also presented.

The anaerobic digestion operational data presented in this report were obtained either from system operators or from the analysis of samples obtained from the various sites.

This report was prepared for government personnel, universities, industries, engineering firms, private research organizations and individuals attempting to design or evaluate anaerobic digestion technology in Canada.

ABSTRACT

The objectives of this project were to develop a computerized database to contain engineering process design information from anaerobic facilities treating agricultural and industrial wastes in Canada, to develop a digester process monitoring and data collection program, to update the database with operational data and to develop a computer conferencing system for information exchange.

The database is stored on the CoSy Computer Conferencing System, developed and operated by the University of Guelph, and is accessible worldwide through DATAPAC or through other similar public switched packet networks. This database is the only comprehensive summary of Canadian agricultural and industrial anaerobic digestion facilities.

A state-of-the-art review of anaerobic digestion technologies was prepared, and a discussion of the current trends in the agricultural and industrial sectors in Canada, the United States and Europe is presented.

An assessment was performed to determine the economic feasibility of employing anaerobic digestion systems for agricultural and industrial applications. For a 2200 sow farrow-to-finish swine operation, a breakeven power cost was estimated to be $0.081/kW.hr with heat recovery. For a 3600 head dairy cow operation, a breakeven power cost was estimated to be $0.088/kW.hr and $0.075/kW.hr for an 8000 head beef cattle operation. These breakeven power cost estimates are well above the current power costs in most provinces in Canada.

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EXECUTIVE SUMMARY

Anaerobic digestion technology has been applied to the treatment of municipal wastes for many years. Recently, because of rising energy and feed costs and more stringent environmental regulations, this technology has been applied to a number of agricultural and industrial wastes. The engineering design and operational conditions at anaerobic digestion facilities in Canada are not readily available or are published in a number of formats making comparisons between facilities difficult. The objectives of the project were to develop a computerized database to contain engineering design information from anaerobic digestion facilities in Canada, to develop a digester monitoring program to update the database with current operational data and to develop a conferencing system for information exchange.

Federal and provincial government officials, universities, engineering firms and individuals involved in anaerobic digestion technology were contacted in order to establish an inventory of anaerobic digestion systems in Canada. An extensive literature review was also conducted. The information was collected in the form of a questionnaire, compiled into a standard format and entered into ASCII data files on an IBM-PC. The information was edited and then uploaded into the CoSy Computer Conferencing System, developed and operated by the University of Guelph, Guelph, Ontario. The Canadian Applied Anaerobic Digestion Technology Data Base is accessible worldwide through DATAPAC, or through other similar public switched packet networks.

The long-term digester monitoring program began in January 1986 and was developed to obtain current operational data and anaerobic digestion plant operator comments to update the database.

The database contains information from sixteen full-scale anaerobic digesters. Of these, eleven digesters are in full operation. A summary of the operational performance of the digesters that were monitored in 1986 is presented.

A state-of-the-art review of anaerobic digestion technology design configurations currently being used to treat agricultural and industrial wastes is presented.

Current and future trends in anaerobic digestion technology in the agricultural and industrial sectors in Canada, the United States and Europe are discussed.

An assessment was performed to determine the economic feasibility of anaerobic digestion systems for agricultural and industrial applications. Current trends in the agricultural

sector indicate that the installation of anaerobic digestion systems for energy production and farm energy savings will not be economically feasible in the foreseeable future. It is anticipated that the motivation for installing anaerobic digestion systems will be odour reduction for site-specific applications, unless energy prices increase dramatically. Current trends in the industrial sector indicate that anaerobic digestion technology is being considered as an effective method of wastewater treatment for pollution abatement and a less costly alternative to aerobic treatment.

RÉSUMÉ

Les déchets urbains sont traités depuis longtemps par digestion anaérobie. L'application de cette technique a récemment été élargie aux déchets agricoles et industriels, en raison des prix croissants de l'énergie et des aliments pour animaux, ainsi que des règlements stricts de protection de l'environnement. Il est difficile d'obtenir et de comparer, en raison des divergences de présentation, les données relatives à la conception technique et aux conditions de fonctionnement des installations de digestion anaérobie au Canada. Le projet qui a été réalisé visait donc à élaborer une base de données informatisée pour y verser les caractéristiques techniques des installations de digestion anaérobie au Canada, à concevoir un programme de surveillance des digesteurs qui permettrait d'ajouter dans la base les données actuelles de fonctionnement et à mettre au point un système de téléconférence pour échanger les renseignements.

On a communiqué avec les agents fédéraux et provinciaux, les universités, les bureaux d'études et les particuliers qui s'intéressent à la filière de la digestion anaérobie afin d'établir un répertoire des digesteurs au Canada. On a aussi fait une revue approfondie de la littérature. Les données recueillies à l'aide d'un questionnaire uniformisé ont été introduites dans les fichiers ASCII sur un PC de IBM. Les données ont été éditées, puis chargées sur le système de

téléconférence informatisée CoSy, mis au point et exploité par l'Université de Guelph en Ontario. Par l'entremise du réseau DATAPAC ou d'un autre réseau public de communication de paquets, il est possible d'accéder à la base de données sur les applications canadiennes de la digestion anaérobie partout dans le monde.

Le programme de surveillance à long terme des digesteurs, commencé en janvier 1986, a été élaboré de façon à obtenir des données actuelles sur le fonctionnement des installations ainsi que les observations des exploitants, renseignements qui serviront à mettre à jour la base de données.

Celle-ci contient des renseignements sur 16 digesteurs anaérobie en vraie grandeur, dont 11 fonctionnent à plein régime. Le rapport présente le résumé des données de rendement des digesteurs contrôlés en 1986.

Le rapport indique aussi les caractéristiques actuelles de conception des digesteurs utilisés pour traiter les déchets agricoles et industriels.

Il traite des tendances du moment et de celles qui se dessinent dans les applications agricoles et industrielles de la technique de digestion anaérobie, au Canada, aux États-Unis et en Europe.

Par ailleurs, on a évalué la faisabilité économique de la technique dans les applications agricoles et industrielles. Il semble que l'emploi de la technique pour produire et économiser l'énergie dans les exploitations agricoles ne se justifiera pas, dans un avenir rapproché, sur le plan économique. A moins que les prix de l'énergie ne montent en flèche, on prévoit que les digesteurs seront plutôt installés à certains endroits en vue de réduire les odeurs dégagées par les déchets. Dans le secteur industriel, la tendance est d'employer la technique de la digestion anaérobie comme moyen de traiter les eaux usées pour réduire efficacement la pollution et comme solution de rechange, moins coûteuse, au traitement aérobie.

1.0 INTRODUCTION AND BACKGROUND

In the past, the economic incentives for the development of alternative energy sources in Canada have not been as great as in other industrialized countries because of Canada's abundant supply of energy resources and subsequent lower than average energy costs. However, a goal of complete energy self-sufficiency by 1990 was established under the federal government's National Energy Program. Several research and development programs were created to support self-sufficiency through energy conservation and production from alternative energy sources such as biomass.

In 1977, the National Research Council of Canada was assigned the task of managing the Bioenergy Research and Development Program. Gasification, liquefaction, combustion and biochemical conversion were identified as priority conversion technologies and sub-programs were established to develop these technologies.

In Canada, the National Research Council has been the centre of fundamental research in the field of anaerobic digestion technology. Since 1977, additional government departments, universities, industries and other private sector organizations have become actively involved in anaerobic digestion technology research.

Anaerobic digestion technology has been applied to the treatment of municipal wastes for many years. Recently, because of the interest in renewable energy production and energy conservation, the technology has been applied to a number of agricultural and industrial wastes as well. In Canada, there are twenty-three, full-scale, anaerobic digestion systems at twenty sites treating a variety of agricultural and industrial wastes.

During 1985/1986, the Canadian Applied Anaerobic Digestion Technology Database and Monitoring Program was developed to monitor full-scale anaerobic digestion systems operating on agricultural and industrial wastes in Canada and to provide a forum for information exchange.

An inventory of anaerobic digestion systems in Canada was established by contacting federal and provincial government officials, universities, engineering firms and individuals involved in anaerobic digestion technology. An extensive literature review of project reports, presentations, journals and other publications was conducted.

To assist in the collection of the design and historical data for each of the facilities, a standard questionnaire was developed. Information available from the literature was filled in and the questionnaires were mailed to the appropriate contact person for each digestion system for verification of the data and completion of the information.

The CoSy Computer Conferencing System, developed and operated by the University of Guelph, was selected for the storage of the data collected during the study. The CoSy system was selected because it is currently being used for a wide variety of similar conferences, is relatively user friendly and is accessible worldwide.

The CoSy Computer Conferencing System is organized into conferences. The conferences each contain topics and each topic contains one or more messages. New information is added to a Totic in the form of a new message. The organizational structure of the Canadian Applied Anaerobic Digestion Technology Database is illustrated in Figure 1. The database contains six conferences. Each conference (except INTRO and DISCUSS) contains one topic for each anaerobic digestion facility. Nineteen anaerobic digestion systems are included in the database. A list of the anaerobic digestion facilities included on the database is presented in Table 1. The six database conferences are as follows:

1) Introduction (INTRO)

   This conference is an introduction to the database. It contains a list of the conferences and a brief description of each.

2) Digester Design Information (DIGESTERDESIGN)

   This conference contains technical design information about anaerobic digestion systems constructed in Canada. Information such as digester design characteristics (digester type and size, hydraulic retention time, operating temperature, loading rate, etc.), biogas utilization, costs (capital, operation and maintenance, and estimated savings) and design and operation problems, is included.

3) Current Operating Conditions (OPCONDITIONS)

   This conference contains information about the current operating conditions at each site, as well as, operator notes and observations.

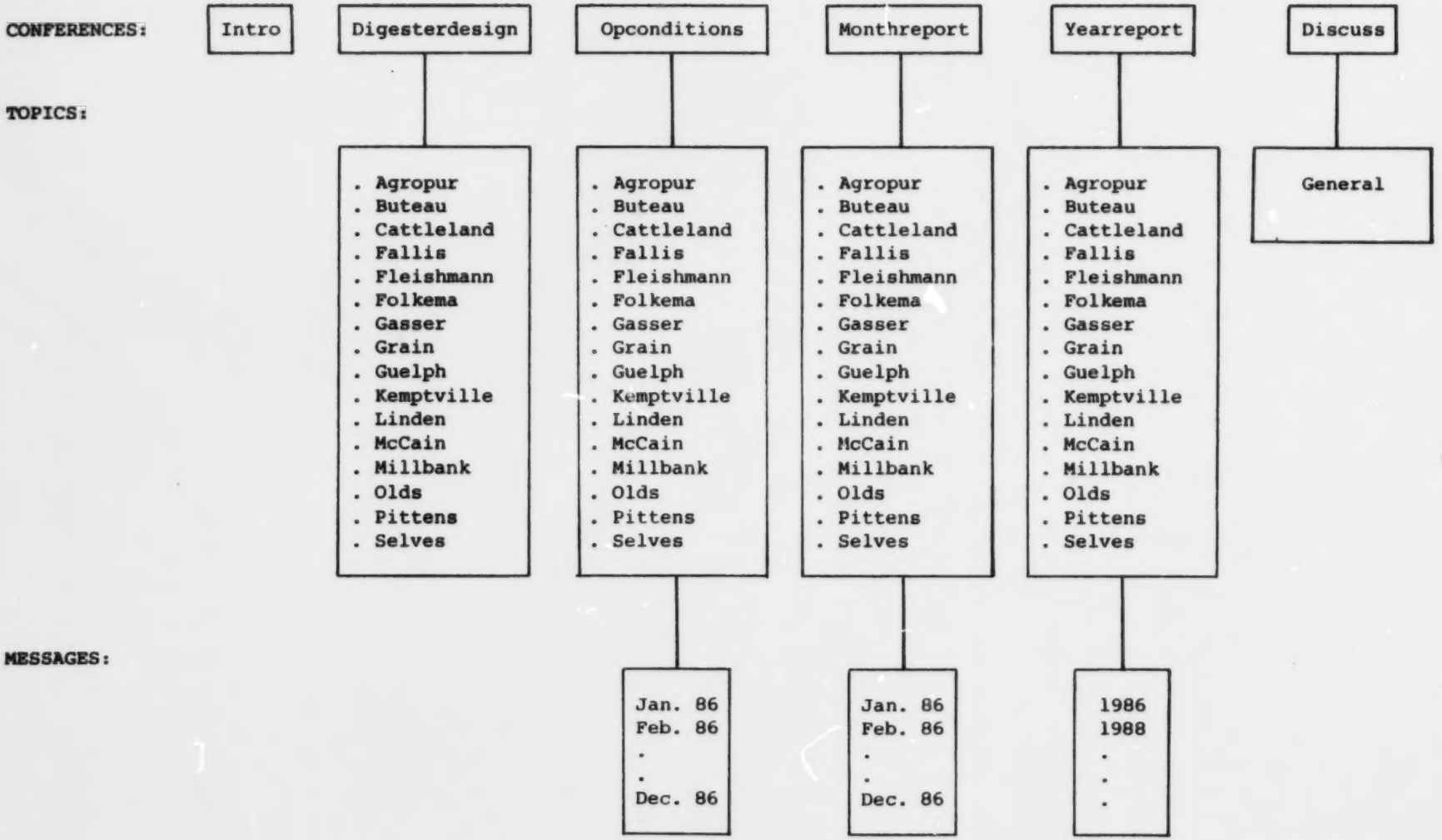

Figure 1
ORGANIZATIONAL STRUCTURE FOR THE CANADIAN ANAEROBIC DIGESTION TECHNOLOGY DATABASE

Table 1
CANADIAN ANAEROBIC DIGESTION FACILITIES

Facility	Location	Type of Operation	Waste Treated	Digester Type	Topic Name
1. Agropur Cooperative Agro-Alimentaire	Notre-Dame-du-Bon-Conseil, Quebec	Cheese Plant	Plant Wash Water	Upflow Anaerobic Sludge Blanket	AGROPUR
2. Buteau and Tremblay Farm (CRIQ)	St. Henri-de-Levis, Quebec	Farm	Swine	Fixed Film	BUTEAU
3. Cattleland Ontario Inc.	Petersburg, Ontario	Farm	Beef Cattle Manure	Completely Mixed	CATTLELAND
4. Fallis Farm	Millbrook, Ontario	Farm	Swine Manure	Completely Mixed	FALLIS
5. Fleishmann's Yeast Ltd.	Calgary, Alberta	Bakers Yeast Plant	Waste Beer	Anhybrid (UASB and Fixed Film)	FLEISHMANN
6. Folkema Farm	Ingersoll, Ontario	Farm	Swine Manure	Fixed Film	FOLKEMA
7. Gasser Farms Ltd.	St. Pierre-de-Veronne-a-Pike-River, Quebec	Farm	Dairy Cattle Manure	Mixed Plug Flow	GASSER
8. Industrial Grain Products, a division of John Labatt Ltd.	Thunder Bay, Ontario	Wheat Starch Plant	Wheat Starch Processing Waste	Completely Mixed	GRAIN
9. Kemptville College of Agricultural Technology	Kemptville, Ontario	College Farm	Beef Cattle Manure	Completely Mixed (originally fixed film)	KEMPTVILLE
10. Linden Lee Farms	Cornwall, P.E.I.	Farm	Swine Manure	Completely Mixed	LINDEN
11. McCain Foods Ltd.	Florenceville, New Brunswick	Food Processing Plant	Potato Processing Waste	Bulk Volume Fermenter	MCCAIN
12. Millbank Cheese & Butter Ltd.	Millbank, Ontario	Cheese Plant	Cheese Whey	Completely Mixed	MILLBANK
13. Olds College	Olds, Alberta	College Farm	Swine & Dairy Cattle Manure	Completely Mixed	OLDS
14. Pittens Farms Ltd.	Cambridge, Ontario	Farm	Dairy Cattle Manure	Completely Mixed	PITTENS
15. Selves Farms Ltd.	Fullarton, Ontario	Farm	Swine Manure	Completely Mixed	SELVES
16. University of Guelph, Arkell Research Station	Guelph, Ontario	University Farm	Swine Manure	(i) Completely Mixed (ii) Completely Mixed	GUELPH

(KIR7/100W)

4) Monthly Data Report (MONTHREPORT)

Statistics on current operating performance, such as influent and effluent characteristics, biogas quality and operational data (biogas quantity, operating temperatures, etc.) recorded at the various sites, are summarized on a monthly basis.

5) Yearly Data Report (YEARREPORT)

Statistics collected at the various sites will be summarized yearly from the monthly reports.

6) Discussion Forum (DISCUSS)

Questions, comments and queries can be entered on the database by users.

The data collected from the questionnaires was compiled into a standard format and uploaded to the appropriate conference and topic in the database.

A digester monitoring program was established to obtain current operational data and operator comments from the various anaerobic digester facilities. The program involved obtaining operational monitoring sheets and records from sites where this information was collected and recorded. Where no operational records were being kept, monthly samples were collected.

The development of the database and monitoring program is described more fully in an interim report prepared for this project. The correct citation for the report is:

> Stickney, A.R. and D.M. Prairie, CANVIRO Consultants Ltd. Long-Term Monitoring and Database Development for Applied Anaerobic Digestion Technology in Canada. Interim Report for Contract File #51SZ.23216-5-7097. Renewable Energy Division; Energy, Mines and Resources Canada, Ottawa, Ontario, 1986, (111 pp.).

A manual entitled "Canadian Applied Anaerobic Digestion Technology Data Base User's Manual" was also prepared.

1.1 Project Objectives

The overall objectives of the project were to develop a computer database containing historical design information and current operational data from Canadian anaerobic digestion facilities, and to make this information available to government personnel, engineering firms, industries and individuals attempting to design or evaluate this technology.

The specific objectives of the project were as follows:

1. Phase I - Develop an inventory of full-scale Canadian anaerobic digestion systems treating agricultural and industrial wastes and establish a computerized database to contain historical design data;

2. Phase II - Develop and implement a long-term monitoring and data collection program for Canadian anaerobic digestion systems and update the database with the information collected;

3. Phase III - Prepare and present the project concept at the Fourth International Symposium on Anaerobic Digestion in Guangzhou, China;

4. Phase IV - Implement the long-term monitoring and database management programs;

5. Phase V - Transfer the acquired information through liaison with other organizations;

6. Phase VI - Prepare statistical summaries and an annual report.

The specific objectives of this annual report are as follows:

1. Outline the status of each full-scale anaerobic digestion system treating agricultural or industrial waste in Canada;

2. Summarize the operational data collected during the anaerobic digester system monitoring program from January to December 1986;

3. Discuss database user activity;

4. Conduct a "state-of-the-art" review of anaerobic digestion system designs;

5. Discuss the economics of anaerobic digestion in Canada;

6. Discuss anaerobic digestion technology for energy production versus pollution abatement;

7. Discuss current and future trends in anaerobic digestion technology in Canada, the United States and Europe.

2.0 OPERATIONAL PERFORMANCE OF CANADIAN ANAEROBIC DIGESTION SYSTEMS DURING 1986 AND CURRENT STATUS

The following is a summary of the operational performance during 1986 of the anaerobic digestion systems included in the database and the current status of each system. A summary of the operational performance of the eight systems monitored is presented in Table 2. Summaries of the operational data for each of these systems are presented in Appendix A.

Agropur Cooperative Agro-Alimentaire

The two reactors at Agropur were temporarily shut down for part of 1986. The upflow anaerobic sludge blanket (UASB) reactor was shut down for repairs until September 1986. The downflow stationary fixed film (DSFF) reactor was converted to a UASB reactor because of blockages experienced with the clay block fixed film media. It was in full operation by January 1987.

The original UASB reactor was monitored in 1986 under an in-house program. Summaries of the operational data were prepared and forwarded monthly to CANVIRO by Agropur personnel.

Buteau and Tremblay Farm

This downflow stationary fixed film (DSFF) reactor was monitored in 1986 by the Centre de Recherche Industrielle du Quebec (CRIQ) under contract to Agriculture Canada. Monthly summaries of the operational data were prepared and forwarded to CANVIRO by CRIQ personnel.

The monitoring program ended on March 31, 1987, and the contract was not renewed. Future plans for the facility are undecided at this time.

Cattleland Ontario Inc.

The system is currently shut down.

Fallis Farm

The system is currently shut down.

Table 2

SUMMARY OF THE OPERATIONAL PERFORMANCE OF THE ANAEROBIC DIGESTION SYSTEMS MONITORED IN 1986

System	% Removal														
	Total Solids			Total Volatile Solids			Total Suspended Solids			Biochemical Oxygen Demand			Chemical Oxygen Demand		
	Mean	SD*	n**	Mean	SD*	n**	Mean	SD*	n**	Mean	SD*	n**	Mean	SD*	n**
Agropur Cooperative Agro-Alimentaire	-	-	-	73	11.7	4	82	0	1	81	7.9	3	83	5.0	4
Buteau and Tremblay Farm	30	12.7	10	34	15.3	10	-	-	-	-	-	-	44	12.8	10
Gasser Farms Ltd.	35	0	1	38	0	1	-	-	-	-	-	-	45	0	1
Kemptville College	37	18.6	6	42	17.4	6	-	-	-	-	-	-	53	7.4	3
Millbank Cheese & Butter Ltd.	73	4.8	8	75	2.5	2	-	-	-	87	4.7	7	79	9.3	11
Olds College	39	4.5	3	48	4.3	3	-	-	-	-	-	-	43	5.1	3
Pittens Farms Ltd.	36	8.0	2	40	8.0	2	-	-	-	-	-	-	44	4.5	2
Selves Farms Ltd.	28	26.6	12	34	33.3	12	-	-	-	-	-	-	54	11.2	12

* SD: Standard Deviation

** n: Number of Values

Fleishmann's Yeast Ltd.

The system is in full operation; however, only design information was available. Arrangements are being made to obtain monthly operational data.

Folkema Farm

The system is currently shut down because of a shortage of manure on the farm. To operate the digester, manure would have to be hauled from a nearby farm and this is not feasible in the winter.

MacLaren Engineers is planning to begin a monitoring program in late Spring 1987, to be funded by Agriculture Canada.

Gasser Farms Ltd.

The system was monitored in 1986 by Urgel Delisle and Associates under contract to Agriculture Canada. Monthly summaries of the operational data were prepared and forwarded to CANVIRO by Urgel Delisle personnel.

The monitoring program ended on March 31, 1987, and was not renewed. Future plans for the facility are still undecided.

Industrial Grain Products

The system is in full operation; however, only design information was available. Arrangements are being made to obtain operational data.

Kemptville College of Agricultural Technology

The facility was shut down in June 1986. Prior to the closure of the facility, the system was monitored by CANVIRO Consultants under contract to Agricultural Canada and the Ontario Ministry of Agriculture and Food. Future plans for the facility are still undecided.

Linden Lee Farms

The system is currently shut down. A monitoring and system evaluation program to be performed by CANVIRO Consultants under contract to Energy, Mines and Resources Canada has been delayed by the construction of a farrowing barn/nursery and the installation of a wood chip burner at Linden Lee Farms. It is anticipated that the monitoring program will begin in June 1987.

McCain Foods Ltd.

The system is in full operation, however only a few design parameters were available.

Millbank Cheese and Butter Ltd.

The system was monitored by CANVIRO Consultants under contract to Energy, Mines and Resources Canada until August 31, 1986. As of September 1986, digester influent, effluent and biogas samples were collected monthly and analyzed as part of the database digester monitoring program. Operational data recorded onsite was summarized and added to the database along with the laboratory analysis results.

Olds College

As of October 1986, monthly composite influent and effluent and biogas samples were collected and analyzed as part of the database digester monitoring program. Operational data recorded onsite were summarized by the operator and forwarded monthly.

Pittens Farms Ltd.

The system was monitored by CANVIRO Consultants, under contract to the Ontario Ministry of Agriculture and Food, from September until December 31, 1986.

Selves Farms Ltd.

During 1986, digester influent and effluent and biogas samples were collected monthly and analyzed as part of the database digester monitoring program. Operational data recorded onsite was summarized and added to the database along with the laboratory analysis results.

University of Guelph - Arkell Research Station

In the fall of 1986, a virus spread through the swine barn at the research station and the building had to be depopulated and disinfected. As a result, no manure was available to operate the digesters. It is anticipated that the intermittent mix digester will be started up in the near future.

Other anaerobic digestion systems not included in the database:

Cavendish Farms

The facility at New Annan, P.E.I. is in full operation; however, no information was available.

Hardee Farms International Ltd.

Hardee Farms, a vegetable processing plant near Lambeth, Ontario closed in September 1985.

LEL Farms Ltd.

The facility in Guelph, Ontario is in operation.

Lakeview Water Pollution Control Plant

This system in Mississauga, Ontario, is in full operation treating thermal conditioning process liquors. Arrangements are being made to obtain design information and operational data.

3.0 SUMMARY OF THE DATABASE AND COMPUTER CONFERENCING SYSTEM USER ACTIVITY FOR 1986

The initial database participants were mainly anaerobic digestion system owners. Many of these people, especially those on farms, did not have a computer or modem to access the database. Other participants had access to computer facilities, but they were not familiar with the operation of a computer and still others were interested in accessing the information, but were awaiting the delivery of computer equipment. A considerable effort was made during the first several months of 1986 to identify the appropriate participants, to ensure that they had the required computer hardware and software and to train them to use the computer equipment to access the database.

During 1986, eighteen of the thirty participants accessed the database. Currently, there are fourteen participants, and of these approximately seven access the information regularly (ie. at least once every two weeks). From the CoSy Computer Conferencing System Usage Summaries, prepared monthly by the University of Guelph's Communication Services, the total connect time for 1986 was 65 hours. This does not include the connect hours for participants that are accessing the database with codes that are either privately funded or funded as part of another project. During the first four months of 1987, the total connect time was 48 hours.

4.0 STATE-OF-THE-ART REVIEW OF ANAEROBIC DIGESTION SYSTEMS

4.1 Anaerobic Digestion System Design Configurations

There are several anaerobic digestion system design configurations currently being used to treat both industrial and agricultural wastes. The following is a brief description of some of the most commonly used configurations.

4.1.1 Plug Flow

Plug flow systems generally consist of a long, narrow trench (earthen or concrete) with a flexible cover for biogas containment and temporary storage. Figure 2 illustrates a typical plug flow design configuration. The digester is generally heated using a hot water heat exchanger located in, or near, the centre or the side walls of the trench (Winfield, 1986). No external mixing is provided; however, some natural cross-sectional mixing is obtained by the thermal overturn created by the heat exchange piping and the release of biogas bubbles during digestion (CEDSI, 1983).

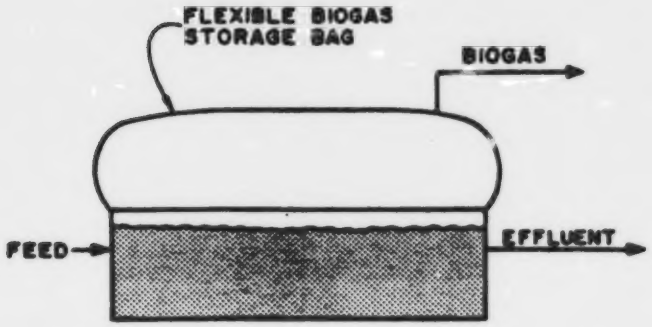

Figure 2
TYPICAL PLUG FLOW REACTOR

High concentration wastes work best with these systems. Dilute wastes, with total solids concentrations of less than 10 percent, tend to settle into layers, which reduce the digester volume, and tend to form a floating scum, which traps the rising biogas (Winfield, 1986; MacDonald, 1982).

The influent waste is fed into one end of the trench and effluent is simultaneously discharged from the other. The trench is often sloped and the force of gravity is used to move the digesting material through the system in the form of a "plug." A portion of the effluent is sometimes recycled in order to inoculate the influent (Winfield, 1986; MacDonald, 1982; Timbers and Marshall, 1981).

Plug flow systems operate at relatively long retention times of 25-30 days.

4.1.2 Completely Mixed

The completely mixed digestion system consists of a vertically oriented, cylindrical, sealed tank (Figure 3). The most commonly used construction material is reinforced concrete, although other materials have been used as well. When possible, the tank is designed such that its diameter equals its height in order to minimize the surface area to volume ratio and thus reduce heat losses. The elevation of the digestion tank varies from completely below grade to above grade depending on soil type and water table. The advantages of installing the tank below grade are reduced heat loss and the ability to use gravity feed. The major disadvantage is limited access to the tank (Winfield, 1986).

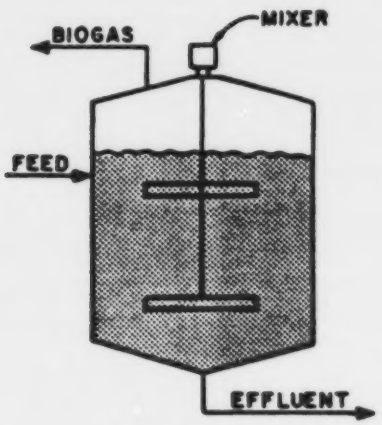

Figure 3
TYPICAL COMPLETELY MIXED REACTOR

The digester contents are generally heated using a hot water heat exchange system or by live steam injection directly into the tank contents (MacDonald, 1982).

The tank contents are mixed using a variety of mixing systems including mechanical mixing systems, such as propeller type mixers or submersible sewage pumps, and gas mixing systems, such as draft tubes or diffusers. Mixing is usually done on an intermittent basis to minimize foaming and energy use (Winfield, 1986; CEDSI, 1983).

The completely mixed digester is capable of handling a wide range of waste concentrations. The influent waste flows by gravity, or is pumped, into the digestion tank and an equal amount of effluent is discharged. The biogas produced is collected and removed from the headspace at the top of the digestion tank.

As the retention time of the completely mixed system is lowered, a point is reached where the bacterial growth rate is lower than the rate of bacterial displacement by the incoming waste. This is called the "wash out point" and is usually recognized as the point at which an increase in the feed rate results in a decrease in the biogas production and volatile solids removal.

Average hydraulic retention times ranging from 10 to 20 days are tolerated without wash out, but because of the intense mixing, some particles are removed from the system shortly after entering, whereas others remain much longer than the average retention time. Toxic substances and shock loads are diluted by mixing, but in general, the completely mixed system is less tolerant to changes in feed or other operating conditions than are other digester configurations (Winfield, 1986; CEDSI, 1983).

4.1.3 Fixed Film

The fixed film digestion system consists of a cylindrical or rectangular tank. The tank is filled with a fixed film media exhibiting a high surface area to volume ratio. A wide variety of materials such as PVC, ABS, fibreglass, reinforced plastic, rubber, glass or clay products can be used as the packing or fixed film material. The microorganisms attach themselves to the media and degrade the waste as it passes. A schematic of a typical fixed film reactor is shown in Figure 4.

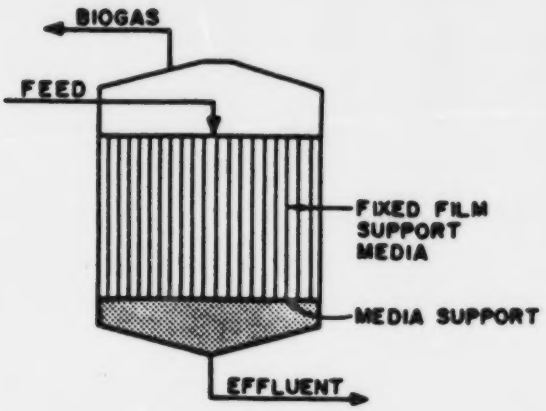

Figure 4
TYPICAL FIXED FILM REACTOR

Typically, the digester is heated using hot water or steam. The release of the biogas and the thermal overturn caused by the heat exchange piping provides some natural mixing as in the plug flow system.

Fixed film systems work best with low strength wastes (less than five percent total solids) and require pre-screening of concentrated, fibrous wastes to prevent media blockage. However, when pre-screening is employed, the overall biogas potential of the waste is reduced, as the screened material contains volatile solids which would otherwise be available for biogas production (Barclay, 1986; Winfield, 1986).

Fixed film digesters can be of the upflow mode, where the influent is introduced through the bottom of the reactor and the effluent is removed through the top, or the downflow mode, where the influent is introduced through the top and moves downwards. Both modes of operation tolerate similar loadings and hydraulic retention times, but the downflow mode is less subject to media plugging. The influent is generally pumped to the digester, although the tank may be located below grade and the waste fed by gravity. As in the completely mixed system, the biogas is collected in the headspace at the top of the tank (CEDSI, 1983; Timbers and Marshall, 1981).

The fixed film media provides a surface to which the bacteria can attach themselves, and therefore the microorganisms are not washed out of the digestion tank as readily as in the completely mixed system. Start-ups are long, and it may take up to six months to develop a biofilm on the media. However, once the biofilm is established, a considerably larger,

viable, bacterial population can be maintained in the digester and the quantity of waste that can be processed per unit volume of digester increases. Because of the high solids retention time maintained, fixed film digesters adjust well to changes in both rate of flow and wastewater characteristics (CEDSI, 1983).

The increased waste volume fed to the digester is only limited by the number of viable organisms available on the surface of the media. In many applications, retention times of one to two days, and less, have been obtained. The lower retention time results in a smaller tank size requirement and thus, reduced capital and heating costs. However, the additional cost of the fixed film media and support system must be weighed against the reduced cost of downsizing before a complete cost comparison can be made (Winfield, 1986).

4.1.4 Upflow Anaerobic Sludge Blanket

The upflow anaerobic sludge blanket system employs the same basic digestion tank configuration as the completely mixed and fixed film systems (Figure 5). However, it depends on the development of a dense granular sludge bed in the bottom portion of the tank, covered by a less dense blanket of suspended solids to degrade the waste (CEDSI, 1983; Kennedy and Guiot, 1986).

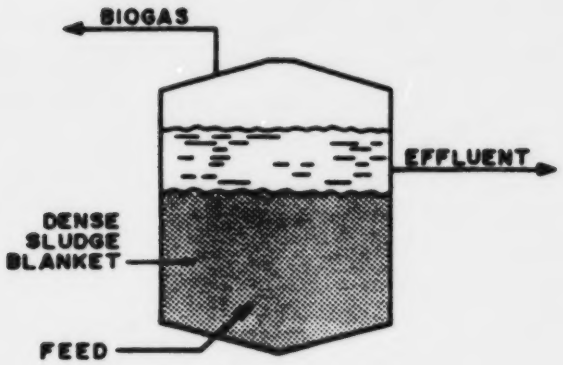

Figure 5
TYPICAL UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR

The system is heated in much the same manner as the completely mixed and fixed film systems using hot water or steam. Usually, the wastewater is heated prior to entering the reactor and no internal heating is provided.

Influent waste is introduced through the bottom of the reactor and is degraded as it rises up through the sludge blanket. Mixing of the sludge blanket occurs as a result of the rising biogas and the relatively high upflow velocity of the wastewater. Solids are carried up through the reactor with the biogas, so the top of the tank is equipped with a gas/solids separator which captures the solids allowing them to settle back to the sludge blanket. An efficient gas/solids separator is imperative as a significant loss of solids inevitably results in an upset of the system (CEDSI, 1983; Kennedy and Guiot, 1986).

The system works best with low to medium strength, soluble or low suspended solid wastes and it is more sensitive to sudden changes in the waste characteristics. Most systems are capable of handling a two to three fold range of flow and waste strength. Usually the wastewater is acidified in an equalization tank or acid reactor prior to pumping to the UASB reactor. The system requires a higher level of operator skill, but is capable of very high removal efficiencies and is very cost competitive in many applications. Start-up is difficult and requires special attention during the development of the sludge blanket. The advantage of the upflow sludge blanket system is that once a sludge bed is established, it is capable of maintaining a greater concentration of active biomass than most other configurations (CEDSI, 1983; Kennedy and Guiot, 1986).

4.1.5 Hybrid

There are a wide variety of hybrid digester configurations available. They all consist of a combination of the upflow sludge blanket and the anaerobic filter and are designed to use the advantages of suspended growth and fixed film to maintain a strong, active biomass (Love, 1986; Crawford, 1986). Figure 6 illustrates a typical hybrid system.

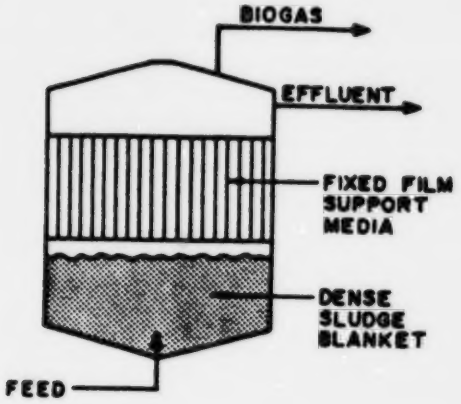

Figure 6
TYPICAL HYBRID REACTOR

In general, the bottom two thirds of a typical hybrid reactor contains a sludge blanket and the top third contains a fixed film media. The fixed film media can be randomly packed, similar to an anaerobic filter, or oriented in almost any configuration. A wide variety of materials such as PVC, ABS, fiberglass, reinforced plastic, rubber, glass or clay products can be used as the packing material. The system is usually operated in the upflow mode with influent being introduced through the bottom of the reactor and effluent being removed from the top. In some cases, effluent is recycled to the sludge blanket. The biogas produced travels up through the reactor and is recovered through the top. As in the upflow sludge blanket design, some of the solids are carried up through the sludge blanket with the biogas. These solids can accumulate in the fixed film media and cause operational problems (Kennedy and Guiot, 1986; Crawford, 1986; Love, 1986).

4.1.6 Anaerobic Contact Process

The contact process design is very similar to the completely mixed design with the addition of solids recycling. When the effluent is discharged from the system, the solids are separated out using a liquid/solid separator and returned to the reactor (CEDSI, 1983). Very high quality effluent can be obtained, but the system is usually very dependent on the liquid/solid separation process.

As with the other reactor configurations described above, the contact process system is heated with hot water or steam.

The contact process system works best with intermediate to high concentration wastes, as low concentration wastes make adequate solids recycling difficult (CEDSI, 1983).

Because the solids are recycled back to the reactor, the solids retention time can be controlled independently of the hydraulic retention time and therefore, the hydraulic retention time can be greatly reduced. Typical hydraulic retention times for anaerobic contact processes range from 0.5 to 4 days compared to the completely mixed system ranging from 10 to 20 days. The reduced hydraulic retention time results in smaller, less expensive reactor volume requirements (CEDSI, 1983).

4.1.7 Fluidized Bed

Fluidized bed reactors are high rate systems in which bacteria are grown on small particles such as sand or carbon. Liquid waste is pumped through the system at a high velocity causing the particles to become suspended or fluidized. The suspended particles maintain a very high surface to volume ratio which enables a substantial active biofilm to develop (CEDSI, 1983; Sutton, 1986). Figure 7 illustrates a typical fluidized bed reactor.

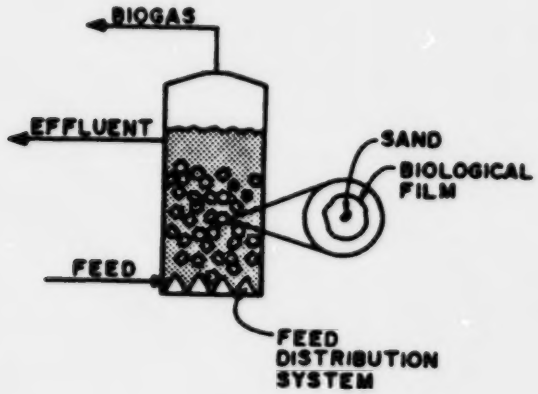

Figure 7
TYPICAL FLUIDIZED BED REACTOR

As with most fixed film systems, the fluidized system works best with low concentration wastes. The influent is pumped up through the fixed film particles and the effluent is removed through the top of the reactor. The reactor is equipped with a particle/effluent separator and escaping fixed

film particles are returned to the system. Some of the effluent is also returned to the system in order to inoculate the influent. The biogas is removed through the top of the reactor (CEDSI, 1983; Sutton, 1986).

Typical hydraulic retention times using this type of system range from 12 to 24 hours (CEDSI, 1983).

4.1.8 Anaerobic Lagoon

Anaerobic lagoons offer a low-cost, waste treatment alternative to the reactor-type systems described above. The effluent quality achieved with the lagoons is inferior, and the land requirements are much greater, but the capital costs are low, as are the operating costs and the costs of expansion (CEDSI, 1983).

Most anaerobic lagoons are designed at a depth of 3 to 6 meters in order to maintain anaerobic conditions and to conserve heat. The lagoon contents are not heated and therefore provisions must be made for extra storage space during the winter months in cold climates, when bacterial activity is at a minimum (CEDSI, 1983).

4.1.9 Bulk Volume Fermenter

Bulk volume fermenters (BVF), which are covered anaerobic ponds, offer another low-cost waste treatment alternative to reactor-type systems. BVFs usually consist of a below-grade earthen basin, covered with a floating membrane, operating under a slight vacuum (Landine et al., 1982). The cover provides for biogas collection and minimizes odours and heat losses. Sludge extraction arrangements are often provided to remove settled solids. BVFs are usually followed by a polishing pond or sand filter or some other solids removal device (CEDSI, 1983).

4.2 Agricultural Systems in Canada

4.2.1 Current Trends in the Agricultural Sector

In the past several years the size and intensity of farming operations has increased considerably, resulting in an increased reliance on electricity and fossil fuels and more stringent environmental regulations.

Lapp et al. first promoted the idea of on-farm biogas production as a method of energy self-sufficiency in Canada in 1974, and significant increases in conventional energy costs further increased the interest in anaerobic digestion technology (Winfield, 1985).

Agriculture Canada, under the auspices of the National Energy Program, provided financial assistance for the development and demonstration of on-farm alternative energy projects. The Ontario Ministry of Agriculture and Food and other provincial agricultural ministries were also involved with similar development and demonstration projects.

Of the twenty-three commercial anaerobic digestion systems in Canada, fourteen are located on farms or at agricultural colleges. Nine digesters are located at swine operations (including three reactors at the University of Guelph - Arkell Research Station), two are at beef operations, two at dairy operations and one at a dairy and swine operation.

Six of the nine anaerobic digestion systems at swine operations are of the completely mixed design configuration, two are fixed film and one is a plug flow. The biogas produced from these systems is used to fuel boilers and electrical co-generation systems. One facility has the capability to recover protein and nutrients from the anaerobically digested effluent.

Both anaerobic digestion systems treating beef manure include completely mixed digesters. The biogas produced from these systems is used to fuel boilers and electrical co-generation systems and both facilities have the capability to recover protein and nutrients from the anaerobically digested effluent.

One of the anaerobic digestion systems treating dairy cattle manure is a mixed plug flow digester and the other is a completely mixed digester. The biogas produced from these systems is used to fuel electrical co-generation systems.

The anaerobic digestion system treating dairy and swine manure is a completely mixed digester. The biogas produced from this system is used to fuel a boiler, an engine generator set and an incinerator.

A summary of the reasons given for selecting anaerobic digestion technology by the agricultural facilities included in the database is presented in Table 3.

Of the eleven agricultural facilities surveyed, five listed energy production as the primary reason for selecting anaerobic digestion, four listed waste treatment (ie. pollution abatement) and one each listed odour control and research. The secondary reasons for selecting anaerobic digestion were, in order of importance, energy production, odour control and protein and nutrient recovery.

Table 3
REASONS FOR SELECTING ANAEROBIC DIGESTION TECHNOLOGY
AT CANADIAN AGRICULTURAL FACILITIES

Facility	Primary Reason for Anaerobic Digestion
1. Buteau and Tremblay Farm	Energy Production & Odour Control
2. Cattleland Ontario	Odour Control
3. Fallis Farm	Waste Treatment & Energy Production
4. Folkema Farm	Waste Treatment, Energy Production & Protein Recovery
5. Gasser Farms Ltd.	Energy Production, Waste Treatment & Odour Control
6. Kemptville College of Agricultural Technology	Energy Production & Protein Recovery
7. Linden Lee Farms	Waste Treatment & Energy Production
8. Olds College	Energy Production, Odour Control & Protein Recovery
9. Pittens Farms Ltd.	Energy Production
10. Selves Farms Ltd.	Waste Treatment, Energy Production & Protein Recovery
11. University of Guelph	Research

Current trends in agriculture indicate that the installation of anaerobic digestion systems for energy production and farm energy savings will not be economically feasible in the foreseeable future. Energy prices have not increased to the levels they were projected to reach fourteen years ago. The potential for energy matching (ie. energy consumed on the farm versus energy produced by anaerobic digestion) has also proven to be very poor.

Intensive swine operations appear to have the highest potential for anaerobic technology. The relatively high constant electrical demand and almost year-round heating requirements in the farrowing and nursery areas represent a relatively good match for anaerobic digestion and electrical co-generation.

At beef feedlots, there is a large quantity of manure produced, but a low energy requirement. The energy required at these facilities is for very intensive uses for very short periods of time.

At dairy cattle operations, there is a high energy demand during milking and feeding, but biogas production rates have not been matched with these high consumption periods, often resulting in increased monthly demand charges.

The recovery and utilization of phosphorus and protein from anaerobically digested animal wastes, while being technically feasible, has not provided the economic incentive to install an anaerobic digestion system. The present world grain surplus and subsequent low grain prices in Canada have resulted in a lower displacement/replacement value for the recovered products. Furthermore, existing legislation only permits producers to use the recovered products for their own herds. Since only approximately ten percent of a conventional ration formulation can be replaced with the recovered products, there would be a surplus that would be valueless. Also, existing farm feeding equipment in many areas does not lend itself to handle these recovered products effectively.

While there is no evidence of loss of nutrient value after anaerobic digestion, there is also no evidence available to indicate that anaerobically digested animal wastes are of increased value as fertilizer.

It is anticipated that the motivation for installing anaerobic digestion systems in the future will be odour reduction for site specific circumstances, unless energy prices increase dramatically.

4.2.2 Economics

An assessment was performed to determine the economic feasibility of anaerobic digestion and electrical co-generation systems at a number of different sizes of swine, dairy and beef cattle operations. The results are presented in Tables 4 through 6.

Figures from the Canadian Farm Building Code (1977) were used to estimate total live weight and total manure production. HEATTANK, a computer program developed by CANVIRO,

Table 4
ECONOMIC ASSESSMENT OF ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEMS AT SWINE OPERATIONS

Unit Size	Total Live Weight (kg)	Total Manure Prod'n (m^3/d)	Digester Size (m^3)	Digester Dimensions	Avg. Daily Biogas Prod'n* (m^3/d)	Annual Biogas Energy* (GJ/yr)	Co-Gen. Unit Size (kW)	Annual kW-hr Prod'n* (kW-hr/yr)	Annual Recoverable Heat Energy* (GJ/yr)	Annual Digester Heat Req'mt** (GJ/yr)	Annual Net Heat Energy Available* (GJ/yr)	Estimated Percentage of Heat Usable (%)	Estimated Annual Usable Heat Energy* (GJ/yr)	Total System Capital Cost (000$)	Total Annual Elect. Power* Revenue (000$/yr)	Tot.Ann. Usable Heat Energy* Revenue (000$/yr)	Estimated Total Annual* Revenue (000$/yr)	Total System Annual O&M Cost (000$/yr) ***	Annual Net Cost (000$/yr)	Breakeven Power Cost (no heat recovery) (¢/kW-hr)	Breakeven Power Cost (with heat recovery) (¢/kW-hr)
100	48515	6.5	125	7.3m ø x 3.1m h	102	774	10	63761	356	374	-18	100	-	170	3.5	-0.2	3.5	23.0	19.3	36.1	36.4
225	109345	14.8	250	7.3m ø x 7.3m h	230	1744	25	143707	802	758	44	100	44	205	7.9	0.4	8.3	27.0	18.7	18.8	18.5
550	266915	36.0	750	9.2m ø x 12.2m h	561	4256	60	350795	1958	1727	147	100	147	380	19.3	1.3	20.6	50.0	29.4	14.2	13.8
1100	533665	72.0	1500	13.4m ø x 12.2m h	1121	8509	125	701373	3914	3275	639	100	639	500	38.3	5.7	44.0	67.0	23.0	9.6	8.7
2200	1067330	144.1	3000	18.3m ø x 12.2m h	2241	17019	230	1402745	7829	6182	1647	100	1647	890	77.0	15.0	92.0	118.0	26.0	8.4	8.1

* 340 day/year operation.

** 365 day/year operation.

*** Including amortization of capital (20 years @ 10%).

(KIR7/100W)

Table 5
ECONOMIC ASSESSMENT OF ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEMS AT DAIRY OPERATIONS

Unit Size	Total Live Weight (kg)	Total Manure Prod'n (m^3/d)	Digester Size (m^3)	Digester Dimensions	Avg. Daily Biogas Prod'n (m^3/d)	Annual Biogas Energy* (GJ/yr)	Co-Gen. Unit Size (kW)	Annual kW-hr Prod'n* (kW-hr/yr)	Annual Recoverable Heat Energy* (GJ/yr)	Annual Digester Heat Req'mt** (GJ/yr)	Annual Net Heat Energy Available* (GJ/yr)	Estimated Percentage of Heat Usable (%)	Estimated Annual Usable Heat Energy* (GJ/yr)	Total System Capital Cost (000$)	Total Annual Elect. Power* Revenue (000$ /yr)	Tot.Ann. Usable Heat Energy* Revenue (000$ /yr)	Estimated Total Annual* Revenue (000$ /yr)	Total System Annual O&M Cost (000$ /yr) ***	Annual Net Cost (000$ /yr)	Breakeven Power Cost (no heat recovery) (¢/kW-hr)	Breakeven Power Cost (with heat recovery) (¢/kW-hr)
300	223860	17.1	500	9.2m ø x 8.5m h	352	2594	30	197993	1193	1081	112	100	112	295	10.9	1.0	11.9	38.5	26.6	19.4	18.9
600	447720	34.2	750	9.2m ø x 12.2m h	705	5188	60	396100	2386	1896	490	100	490	380	21.8	4.4	26.2	50.0	23.8	12.6	11.5
900	671580	51.4	1500	13.4m ø x 12.2m h	1057	7781	100	593977	3579	2904	675	75	500	500	32.7	4.5	37.2	67.0	29.8	11.3	10.5
1800	1343160	102.7	3000	18.3m ø x 12.2m h	2115	15562	200	1187957	7159	5448	1711	30	515	890	65.3	4.7	69.9	118.0	48.1	9.9	9.5
3600	2686320	205.4	2x 3000	2-18.3m ø x 12.2m h	4229	31127	400	2375913	14318	2x 5448	3422	16	550	1630	130.7	5.0	135.7	216.0	80.4	9.1	8.8

* 340 day/year operation.

** 365 day/year operation.

*** Including amortization of capital (20 years @ 10%).

(KIR7/100W)

Table 6
ECONOMIC ASSESSMENT OF ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEMS AT BEEF CATTLE OPERATIONS

Unit Size	Total Live Weight (kg)	Total Manure Prod'n (m^3/d)	Digester Size (m^3)	Digester Dimensions	Avg. Daily Biogas Prod'n (m^3/d)	Annual Biogas Energy* (GJ/yr)	Co-Gen. Unit Size (kW)	Annual kW-hr Prod'n* (kW-hr/yr)	Annual Recoverable Heat Energy* (GJ/yr)	Annual Digester Heat Req'mt** (GJ/yr)	Annual Net Heat Energy Available* (GJ/yr)	Estimated Percentage of Heat Usable (%)	Estimated Annual Usable Heat Energy* (GJ/yr)	Total System Capital Cost (000$)	Total Annual Elect. Power* Revenue (000$ /yr)	Tot.Ann. Usable Heat Energy* Revenue (000$ /yr)	Estimated Total Annual* Revenue (000$ /yr)	Total System Annual O&M Cost (000$ /yr) ***	Annual Net Cost (000$ /yr)	Breakeven Power Cost (no heat recovery) (¢/kW-hr)	Breakeven Power Cos (with heat recovery) (¢/kW-hr)
500	200000	11350	250	7.3m ø x 7.3m h	283	2085	25	159096	959	718	241	100	241	205	8.8	2.2	10.9	27.0	16.1	17	15.6
1000	400000	22700	500	9.2m ø x 8.5m h	566	4167	40	318186	1917	1315	602	80	482	295	17.5	4.3	21.8	38.5	16.7	12.1	10.7
2000	800000	45400	1000	11.0m ø x 12.2m h	1133	8337	100	636371	3835	2484	1351	36	486	465	35.0	4.4	39.4	62.0	22.6	9.7	9.1
4000	1600000	90800	2000	15.9m ø x 12.2m h	2266	16675	200	1272746	7671	4743	2928	17	498	810	70.0	4.5	74.5	109.0	34.5	8.6	8.2
8000	3200000	181600	4000	22.0m ø x 12.2m h	4531	33349	400	2545478	15341	9102	6239	8	500	1450	140.0	4.5	145.5	195.0	49.5	7.7	7.5

* 340 day/year operation.

** 365 day/year operation.

*** Including amortization of capital (20 years @ 10%).

(KIR7/100W)

was used to size the anaerobic digestion tanks according to size of operation and to estimate the biogas production, biogas energy, electrical power production and digestion tank heating requirements for each size. Engine generator set unit sizes were selected according to the estimated biogas production. Annual electrical power production figures were calculated based on the rated generator capacity running at 80% of full load, 24 hours per day, 340 days per year. Of the total biogas energy produced, 28% is converted to electrical energy, 46% is recoverable as heat energy, and the remaining 26% is lost through radiation and the exhaust engine gases. The annual net heat energy available was obtained by subtracting the annual digester heating requirement from the annual recoverable heat energy. Annual usable heat energy figures were calculated by estimating the percentage of the heat recovered that could be used at the different sizes and types of operation. Total system capital costs were estimated by costing the major components and by using figures for systems that have been installed. The total annual electrical power revenue was calculated by multiplying the annual electrical power production by an estimated value of $0.055/kW.hr (an estimate for the cost per kW.hr in Ontario). The total annual usable heat energy revenue was estimated by multiplying the annual usable heat energy by an estimated value for propane of $9.00/GJ. Total system annual operation and maintenance costs were obtained by making estimates for labour, power and equipment repair and maintenance costs and including amortization of capital. Breakeven power costs were calculated with and without heat recovery.

Table 4 summarizes an economic assessment for swine operations from 100 to 2200 sows farrow-to-finish. For a 100 sow farrow-to-finish operation, the breakdown power costs were estimated to be $0.361/kW.hr without heat recovery and $0.364/kW.hr with heat recovery. For a 2200 sow farrow-to-finish operation, the breakeven power costs were estimated to be $0.084/kW.hr without heat recovery and $0.081/kW.hr with heat recovery. Even with a 2200 sow farrow-to-finish operation, the breakeven power costs are well above the current power costs in most provinces.

Similar tables were prepared for dairy and beef cattle operations (Tables 5 and 6). The breakeven power costs for a 3600 head dairy cow operation were estimated to be $0.091/ kW.hr without heat recovery and $0.088/kW.hr with heat recovery. For an 8000 head beef cattle operation, the breakeven power costs were estimated to be $0.077/kW.hr without heat recovery and $0.075/ kW.hr with heat recovery. These estimates are also well above the current power costs in most provinces in Canada.

4.3 Industrial Systems in Canada

4.3.1 Current Trends in the Industrial Sector

In Canada, there are no government assistance programs that specifically support the demonstration of innovative pollution control technologies. There are, however, several programs related to the National Energy Program which include energy production and conservation and resource recovery projects (Hall, 1983). Anaerobic digestion technology is considered to be sufficiently energy efficient to qualify for funding under some of these provincial and federal government programs.

There are nine anaerobic digestion systems treating industrial wastes in Canada. Two of the systems are treating potato processing wastes, two are treating cheese plant wash water (both at the same location), one is treating wheat starch processing waste, one is treating waste beer from a yeast processing plant, one is treating cheese whey and one is treating thermal conditioning process liquors. Another anaerobic digestion system was used to treat vegetable processing wastes, but the processing plant is now closed.

The two anaerobic digestion systems at the potato processing plants are bulk volume fermenters.

Both of the anaerobic digestion systems treating cheese plant wash water are upflow anaerobic/sludge blanket reactors and the biogas produced is used to fuel a boiler.

The anaerobic digestion systems treating wheat starch processing waste and cheese whey are completely mixed reactors. The biogas produced at the wheat starch processing plant is flared and the biogas produced at the cheese plant is used to fuel a boiler.

The systems treating waste beer and thermal conditioning process liquor are hybrid reactors and the biogas produced at these facilities is being flared. The anaerobic digestion system that was used to treat vegetable processing waste was also a hybrid reactor and the biogas produced was flared.

A summary of the reasons given for selecting anaerobic digestion by the industrial facilities included on the database is presented in Table 7.

Table 7
REASONS FOR SELECTING ANAEROBIC DIGESTION AT CANADIAN INDUSTRIAL FACILITIES

	Facility	Primary Reason for Anaerobic Digestion
1.	Agropur Cooperative Agro-Alimentaire	Waste Treatment
2.	Fleishmann's Yeast Ltd.	Waste Treatment
3.	Industrial Grain Products/ John Labatt Ltd.	Waste Treatment, Energy, Production & Odour Control
4.	McCain Foods	Waste Treatment
5.	Millbank Cheese & Butter Ltd.	Waste Treatment & Energy Production

Of the industrial facilities surveyed, all listed waste treatment (pollution abatement) as the primary reason for selecting anaerobic digestion. Some listed energy production and odour control as secondary reasons.

Current trends in the industrial sector indicate that anaerobic digestion technology is being considered as an effective method of wastewater treatment for pollution abatement and a less costly alternative to aerobic treatment. For many wastewaters, there is a considerably lower total energy requirement to treat the waste anaerobically rather than aerobically.

In general, anaerobic digestion technology is applicable to medium to high strength wastewaters (ie. chemical oxygen demand >2000 mg/L). The minimum feasible level of chemical oxygen demand is a function of wastewater temperature (the lower the wastewater temperature, the higher the COD level must be to justify anaerobic digestion).

There is less waste sludge produced from anaerobic digestion compared to aerobic treatment. This is becoming more significant because of increasing sludge disposal costs and the increasing difficulty of obtaining permission from landfill sites to dispose of waste sludges. Also, the dewatering characteristics of anaerobically digested sludge are far superior to those of waste activated sludge.

The capital costs of anaerobic and aerobic treatment systems are similar; however, in cases where the wastewater is at or near digester operating temperature, anaerobic treatment is the less costly alternative.

4.3.2 Economic

In the industrial sector the interest in anaerobic technology has been directed primarily at pollution abatement rather than energy production, although in many cases, energy was the initial attraction to this technology. The technology is capable of substantially reducing the organic loading (biochemical oxygen demand, chemical oxygen demand and suspended solids) from a wastewater at significantly lower operating costs than conventional (activated sludge) wastewater treatment technologies.

The net capital and operating cost differential between anaerobic and aerobic treatment will vary from site to site. The major factors that will influence this cost differential are the wastewater flow rate, biochemical and/or chemical oxygen demand, temperature, pH, and nutrients and mineral concentrations.

The following example in Sections 4.3.2.1 to 4.3.2.3 illustrates the potential savings that may accrue as a result of applying anaerobic versus conventional aerobic treatment to a typical food processing wastewater.

A wastewater characterization program was conducted at a meat packing plant to establish the wastewater strength, flow patterns, temperature and nutrient and mineral balances. Pilot testing of a number of anaerobic technologies was performed and this data was used to establish the anticipated effluent characteristics. The plant discharges its treated effluent to a municipal sewer. The municipality has a sewer discharge bylaw and surcharges the industry for over strength wastewater.

The meat packing plant currently pretreats the wastewater from their packing operation. The manure-bearing wastewaters are collected separately and passed over vibrating screen separators to remove any large particulate matter prior to entering the equalization tank. The solid material collected from the screen is conveyed to a holding tank and disposed of on agricultural land. All the remaining wastewater including the liquid fraction of the manure-bearing line are discharged to an equalization tank located in the wastewater pretreatment building.

The combined wastewater is treated using dissolved air flotation (DAF) to remove fats, grease and oil. The fats, grease and oil are skimmed from the DAF units and returned to the rendering plant. The final effluent from the DAF units is discharged to the municipal sewer but does not meet the discharge levels established by the Regional Municipality of Waterloo.

Wastewaters that do not meet the discharge criteria of 300 mg/L of BOD_5 and 350 mg/L of suspended solids are subjected to a cost recovery surcharge formula as follows:

$$\text{Cost} = \tfrac{1}{2}\,\frac{(BOD_5-300)}{300} + \tfrac{1}{2}\,\frac{(SS-350)}{350} \times \frac{\text{Treatment Cost per 1000 gal}}{} \times \frac{\text{Total Volume}}{1000}$$

In 1985, the treatment cost of 1000 gallons of municipal wastewater in the Regional Municipality of Waterloo was $0.287879. In 1986, the treatment cost increased by 21% to $0.348242/1000 gallons. The 1985 surcharge to the meat packing plant was $101,032. It was estimated that if the effluent quality and total flow were the same in 1986 as they were for 1985, the surcharge would be $122,249.

The Regional Municipality of Waterloo projects that the cost of sewage treatment will continue to increase for the next several years at approximately the same rate experienced from 1985 to 1986.

4.3.2.1 Anaerobic Technology

A preliminary anaerobic treatment system was conceptually designed using the upflow anaerobic sludge blanket (UASB) technology. The system was designed to treat the peak total plant wastewater flow of 13,638 m^3/day and to achieve an effluent quality below the municipal wastewater surcharge limits of 300 mg/L BOD_5 and 350 mg/L of suspended solids. Table 8 summarizes the raw wastewater characteristics used for the conceptual design and the anticipated wastewater characteristics after anaerobic treatment.

Table 8
DESIGN WASTEWATER AND EFFLUENT CHARACTERISTICS FOR THE ANAEROBIC TREATMENT PLANT

Parameter	Wastewater Characteristics	Treatment Effluent Characteristics	
Maximum Flow	13,638 m^3/d		13,638 m^3/d
Average Flow	7,769 m^3/d		7,769 m^3/d
Minimum Flow	4,546 m^3/d		4,546 m^3/d
Total Suspended Solids	410 mg/L	at average flow	235 mg/L
		at peak flow	270 mg/L
BOD_5	736 mg/L	at average flow	200 mg/L
		at peak flow	300 mg/L
pH	8.1		7.0
Average Temperature	29.7		29.7

Results from pilot testing indicated that the UASB reactor could successfully treat the wastewater at the mean wastewater ambient temperature of 29.7°C.

During the study, no pH adjustment was required to maintain reactor contents within the desired 6.5 to 7.5 pH range. The wastewater appeared to have all the essential nutrients and minerals to sustain the anaerobic process and therefore, no additions were required.

Table 9 summarizes the anaerobic treatment system design. The system would consist of two UASB reactors operating in parallel. The reactors would each have an active volume of 1,704 m^3 and would be constructed of reinforced concrete. Under peak flow conditions, the HRT in the reactors would be 6 hours and the mean BOD_5 loading, 2.9 kg $BOD_5/m^3/d$. Under average flow conditions, the HRT would be 10.5 hours and the mean BOD_5 loading, 1.7 kg $BOD_5/m^3/d$.

Table 9
ANAEROBIC TREATMENT PROCESS DESIGN SUMMARY

Unit	Design Description
Anaerobic Reactor	- Technology - upflow anaerobic sludge blanket with internal overflow weir - Two parallel reactors each with the same volume - Material of construction - reinforced concrete - Volume - 1704 m^3 - Reactor height 12.2 m - Reactor active height 12.1 m - Reactor diameter 13.4 m - Hydraulic rise rate (peak flow) 2.0 m/hr = 0.03 m/min - Hydraulic rise rate (average flow) 1.2 m/hr = 0.02 m/min - Hydraulic retention time (peak flow) 6 hours - Hydraulic retention time (average flow) 10.5 hours - Operating temperature 29.7°C (ambient wastewater temperature) - Gravity discharge to sewer - Maximum organic loading 2.9 kg $BOD_5/m^3.d$ - Average organic loading 1.7 kg $BOD_5/m^3.d$
Biogas Storage	- Biogas production 6,370 m^3/day - Biogas methane content 60%

Waste sludge from the system would be blended with the paunch manure and disposed of on agricultural land as fertilizer.

The anaerobic treatment system estimated capital, operating and maintenance costs are summarized in Table 10. Capital costs are included for a reactor control building and an equalization tank.

Table 10
ANAEROBIC TREATMENT SYSTEM COST SUMMARY

Unit Description	Capital Cost	Operating Labour Cost	Maintenance Labour Cost	Power Cost	Material Cost	Total O&M Cost
Anaerobic Reactors (two)	$ 450,000 each	$24,000	$ 1,000	-	$ 2,000	$ 27,000
pH Monitoring Equipment & Temperature Monitoring Equipment	20,000	6,000	2,000	$ 100	2,000	10,100
Biogas Storage & Utilization Equipment	125,000	30,000	10,000	6,000	15,000	61,000
Reactor Control Building	180,000					
Sludge Handling & Storage Equipment	55,000	6,000	1,000	500	2,000	9,500
Feed Pumps & Piping	125,000	-	5,000	18,000	6,000	29,000
TOTAL COSTS	$1,405,000	$66,000	$19,000	$24,600	$27,000	$136,600

The total estimated capital cost for the system is $1,405,000 and the total estimated operating and maintenance costs are $136,600/year.

4.3.2.2 Conventional Extended Aeration Treatment

Three extended aeration treatment configurations were considered for comparison with anaerobic treatment. These include:

1) An extended aeration system with secondary clarification and sludge disposal without sludge treatment;

2) An extended aeration system with secondary clarification and sludge disposal with anaerobic sludge digestion and disposal of the treated sludge;

3) An extended aeration system with secondary clarification and sludge disposal with aerobic sludge digestion and disposal of the treated sludge.

The computer aided design program, CAPDET, was used to assist in the design and costing of each of the configurations. CAPDET is the acronym for Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems and was developed by the U.S. Army Corps of Engineers, with support from the U.S. Environmental Protection Agency (Harris et al., 1982), as a costing tool to prescreen wastewater process alternatives on a least-cost basis. The extended aeration configuration with aerobic sludge digestion had the lowest overall capital cost and operating and maintenance costs and was selected as the conventional waste treatment system to compare with anaerobic treatment.

The effluent quality achievable with anaerobic treatment was selected as the design effluent quality for the extended aeration system. This allowed a direct economic comparison to be made between the anaerobic treatment system and the extended aeration system.

Table 11 summarizes the raw and treated wastewater characteristics. The system was designed to treat a peak flow of 13,638 m^3/day with a peak loading of 10,038 kg BOD_5/day and maintain an effluent quality which exceeds the municipal surcharge limits of 300 mg/L BOD_5 and 350 mg/L suspended solids.

Table 11
WASTEWATER AND EFFLUENT CHARACTERISTICS FOR THE EXTENDED AERATION TREATMENT SYSTEM

Parameter	Raw Wastewater Characteristics	Treated Effluent Characteristics
Maximum Flow	13,638 m^3/d	13,638 m^3/d
Average Flow	7,769 m^3/d	7,769 m^3/d
Minimum Flow	4,546 m^3/d	4,546 m^3/d
Total Suspended Solids	410 mg/L	235 mg/L
BOD_5	736 mg/L	200 mg/L
pH	8.1	8.1
Average Temperature	29.7°C	29.7°C

Table 12 summarizes the extended aeration treatment system design. The extended aeration tank would have a volume of 7,274 m^3 and require 225 kW of power for aeration. The secondary clarifier would be a circular design with a surface area of 415 m^2. The sludge recycle rate for the system would be 50%. The average HRT in the clarifier would be 3.5 hours.

Table 12
EXTENDED AERATION PROCESS DESIGN SUMMARY

Unit	Design Description	
Extended Aeration Unit	Volume	7,274 m^3
	Aeration Power Requirements	225 kW
	Solids Retention Time	4 days
	Sludge Production Rate	0.7 kg solids/kg BOD_5
	Recycle Ratio	50%
	Volumetric Loading	0.8 kg BOD_5/m^3
Secondary Clarifier	Circular Design (diameter)	23 m
	Solids Loading Rate	48.8 kg/m^2
	Surface Area	415 m^2
	Surface Overflow Rate	24.5 $m^3/m^2.d$
	Detention Time	3.46 hours
	Tank Sidewater Depth	2.7 m
	Sludge Volume	364 m^3/d
Aerobic Digester	Volume	910 m^3
	Solids Retention Time	20 days
	Volatile Solids Loading	4.0 kg/m^3
	Oxygen Required	142 m^3/d
Sludge Hauling & Spreading	Volume of Sludge Hauled per day	45.5 m^3/d

The wasted sludge would be aerobically treated to reduce its volume and then hauled away for land application. The aerobic reactor would have a volume of 910 m^3 and a solids retention time of 20 days. The system would generate 45.5 m^3/day of waste sludge.

The estimated extended aeration process costs are summarized in Table 13.

Table 13
EXTENDED AERATION PROCESS COST SUMMARY

Unit Description	Capital Cost	Operating Labour Cost	Maintenance Labour Cost	Power Cost	Total O&M Cost
Extended Aeration Tank	$1,932,000	$60,000	$31,000	$98,500	$189,500
Secondary Clarifier	$557,000	$6,000	$3,000	$3,500	$12,500
Aerobic Digester & Sludge Handling Equipment	$440,000	$19,000	$9,000	$9,000	$37,000
Total	$2,929,000	$85,000	$43,000	$111,000	$239,000

The total estimated capital cost for the extended aeration system is $2,929,000 and the total estimated operating and maintenance cost is $239,000/year.

4.3.2.3 Economic Comparison of Anaerobic Treatment and Extended Aeration Treatment of Total Plant Wastewater

Table 14 summarizes the capital and operating costs for the two systems.

Table 14
SUMMARY OF ECONOMIC COMPARISON BETWEEN ANAEROBIC TREATMENT AND EXTENDED AERATION TREATMENT

Item	Anaerobic Treatment		Extended Aeration Treatment	
	Cost/Revenue	$/kg BOD_5	Cost	$/kg BOD_5
Capital Cost	1,405,000	337	2,929,000	703
Operating Cost	136,600	33	239,000	57
Sewer Surcharge Reduction	122,250	-	122,250	-
Biogas Production Revenue	172,000	41	-	-
Net Operating Cost (surplus)	(157,650)	(38)	116,750	28
Straight-line Payback (years)	8.9	-	None	-

The capital cost for the anaerobic treatment facility is estimated to be $1,405,000 and $2,929,000 for the extended aeration system. Both systems were designed to produce effluent that is below the sewer discharge limits, and thereby eliminate any sewer surcharge costs.

The total O&M costs for anaerobic treatment are $136,000/year and $239,000/year for the extended aeration system.

It is estimated that the anaerobic treatment system will generate approximately 1.8 million cubic meters of biogas per year with an average methane content of 60%. The average cost in 1986 for natural gas at the plant was $0.159006/m³. Based on this natural gas cost, it is estimated that the biogas will have a value of $172,000/year.

The estimated net operating cost for the extended aeration system is $116,705/year, after the elimination of the surcharge and excluding amortization of capital. The estimated net operating revenue for the anaerobic system is $157,650, after the elimination of the surcharge, excluding amortization of capital and with utilization of the biogas.

A simple straight line payback for the anaerobic system is calculated to be approximately nine years.

Anaerobic technology on its own cannot produce the high quality effluent required in most areas to discharge directly to surface water. If high quality effluent is required, additional polishing, using an aerobic process will be necessary. This will increase the overall capital cost and reduce the net operating revenues for the system. However, for most food and related industry wastewaters anaerobic technology provides an excellent pretreatment step at a significantly lower cost per kilogram of BOD_5 removed compared to equivalent aerobic systems.

4.4 Current Trends in the Agricultural and Industrial Sectors in the United States and Europe

4.4.1 Current Trends in the United States

A comprehensive review of 87, commercial-scale, anaerobic, digestion systems in the United States was prepared by John Ashworth, Associates in Rural Development, Inc., in 1985, in support of the Anaerobic Digestion Research Program managed by the Biomass Program Office of the Solar Energy Research Institute.

According to Ashworth, prior to 1977, anaerobic digestion systems in the United States were almost exclusively experimental models for university or private research. The U.S. government launched a major program to support applied research and development of anaerobic digestion technology between 1977 and 1981. The research and development activities were aimed at commercializing systems for farm-scale and feedlot energy production. The U.S. Departments of Energy and Agriculture funded farm-scale and industrial anaerobic digestion technology demonstrations and a program to develop and test new designs, at Cornell University and other research centres. By the end of 1980, sixteen full-scale (anaerobic reactors with volumes greater than 100 m^3) systems had been constructed in the United States (Ashworth, 1985). In 1980, the U.S. Departments of Energy and Agriculture decided to co-sponsor an anaerobic digestion technology demonstration program at ten to twenty proposed swine, poultry, cattle and beef operations. The program, however, was never implemented due to changes in the direction of the Department of Energy's management in 1981.

Nevertheless, the U.S. government's promotional program between 1977 and 1981, along with increasing energy costs and more stringent environmental regulations, did generate a considerable amount of interest in anaerobic digestion technology, and between 1981 and 1984, eleven to eighteen full-scale systems were designed and constructed each year.

In 1985, Ashworth found that, of the 87, full-scale, anaerobic digestion systems constructed in the United States, sixty were in full operation, seven were temporarily shut down for repairs or modifications and a number of others were in various stages of design and development.

There were forty-four full-scale systems operating on farms and eighteen full-scale industrial applications in 1985, in the United States. Of these, twenty-seven were at dairy operations, four at beef operations, six at swine operations, five at poultry operations and two at swine and poultry operations. In the industrial sector, a variety of agricultural, brewery and food processing plant wastes were treated, including sugar beet, potato, stillage and yeast processing wastes.

The most common design configuration at dairy and beef operations was the plug flow or modified plug flow digester. There were twenty-four such systems operating or temporarily shut down in 1985. The remaining seven were completely mixed systems. At the swine operations, there were two completely mixed systems, two anaerobic lagoons and one plug flow system. At the poultry operations, there were three completely mixed systems and two plug flow or modified plug flow systems. At the swine and poultry operations, there was one completely mixed system and a modified plug flow system.

At thirty-one of the agricultural locations, the biogas produced was used to fuel engine generator sets to produce electricity for on-farm use or to be sold to the local utility. At ten locations, the biogas was used to fuel boilers and at three locations, the biogas was used for some other purpose. At many locations, the digester effluent was processed to produce bedding material, potting soil, refeed for non-lactating animals or fertilizer for cash crops.

Several anaerobic digestion system design configurations have been applied to industrial wastes in the United States. In 1985, there were five upflow packed bed reactors, five completely mixed systems, four upflow sludge blanket reactors, two anaerobic lagoons, one downflow packed bed reactor and one fixed film system, treating a variety of industrial wastes.

At fourteen of these locations, the biogas produced was used to fuel boilers; at one location it was used to fuel an engine generator set; at one location it was flared; and at two locations the biogas was used for some other purpose.

Current trends in the United States suggest that environmental quality control pressures will favour the development of anaerobic digestion technology (Pohland and Harper, 1985). Pohland and Harper also indicated that energy from biogas was predicted to assume an increasing share of North American energy budgets, although the intensity of associated research and development would remain inextricably linked and vulnerable to economic and political influences.

Most of the information available on operational, full-scale, agricultural systems indicates a preference for simpler and less costly technologies, such as lagoons, plug flow and intermittently mixed digesters. Hashimoto (1983) suggests that, in order for anaerobic technology to have a wider application, the total and operating costs would have to be reduced and the value of the recovered products would have to increase.

In the industrial sector, anaerobic digestion technology has been receiving increased attention as an effective method of waste treatment and as a means of reducing energy costs. Anaerobic technology is almost always considered as a pre-treatment step prior to the expansion of any industrial wastewater treatment system. This trend is evidenced by the recent construction of several anaerobic digestion systems installed to treat a variety of high-strength industrial wastes.

4.4.2 Current Trends in Europe

Since 1978, the Commission of the European Communities, through its Energy Demonstration Program, has sponsored the construction of forty-eight demonstration anaerobic digestion systems. Of the forty-eight demonstration facilities, nineteen were treating agricultural wastes, seventeen were treating industrial wastes and twelve were treating urban waste and sewage sludge. These systems were to be monitored extensively to provide comprehensive operational data from which problem areas could be identified and effective system operational procedures developed.

Between 1981 and 1984, representatives from Belgium, Denmark, France, The Federal Republic of Germany, Greece, Ireland, Italy, the Netherlands, the United Kingdom and Switzerland identified 546 anaerobic digestion systems in the European Community and Switzerland for a survey commissioned by the Directorate General for Science, Research and Devel-

opment (DG XII) of the Commission of the European Communities within the framework of the Solar Energy Research and Development Program. A three-volume compendium was prepared summarizing the results of the survey (Demuynck and Nyns, 1984).

In 1983, 378 full-scale and forty-two pilot-scale systems treating agricultural wastes and sixty-nine full-scale and twenty pilot-scale system treating industrial wastes were identified.

Sixty-eight percent of the systems treating liquid agricultural wastes employed completely mixed digesters and sixteen percent employed plug flow systems. The remainder were either anaerobic filters, anaerobic contact systems, fixed film systems or two-stage systems.

Twenty-three different industrial wastes, being treated by anaerobic digestion, were identified during the survey, including wastewaters from sugar refineries, slaughterhouses, distilleries, potato processing, leather, and paper industries. The most common technology used to treat industrial wastes was the upflow sludge bed reactor. There were forty-one such systems at the time of the survey. Other technologies included twenty-eight anaerobic contact systems, fifteen fixed film systems and fifteen completely mixed or plug flow systems.

Steel and concrete were the most commonly used materials in the construction of anaerobic digestion tanks. Ninety-one percent of the digestion tanks were insulated and of these, seventy percent used a synthetic material and thirty percent used some type of natural material.

Internal heating systems, such as heating coils and heat exchangers, were installed at sixty-six percent of the facilities and the remainder installed external systems, usually jacketed vessels.

Liquid recirculation was the most commonly selected method of mixing, present in thirty-five percent of the systems, followed by gas recirculation in twenty-five percent, liquid recirculation with mechanical mixing in fourteen percent and mechanical mixing alone in twelve percent.

The majority of the systems used some type of plastic membrane bag for biogas storage. The biogas was often dewatered before it is was used, but seldom scrubbed for hydrogen sulfide and/or carbon dioxide.

Current trends in Europe indicate that anaerobic digestion technology will continue to be used as an effective method of agricultural and industrial waste treatment and energy production. Anaerobic treatment has proven to be very com-

petitive with aerobic treatment in industrial applications. Anaerobic digestion technology, however, has suffered from negative publicity from existing facilities. In most cases, these systems were the first installations constructed by owners or small enterprises and, because of a lack of available design and operational information, the same basic errors were made over and over again. Nyns (1985) recommended that national or regional centres be established to provide digester design, construction and operational information. Nyns indicated that the Commission of the European Communities was planning to hold a symposium to present the results of its extensive demonstration program.

4.5 Comparison Between Current Trends in Canada, the United States and Europe

In the past few years, several state-of-the-art reviews dealing with anaerobic digestion have been prepared worldwide. In Canada, Hall (1983) presented a paper entitled "The Development and Utilization of Anaerobic Technology in Canada"; Winfield (1986) prepared a report entitled "Biogas Production Facilities on Farms - A 1985 Look at Recent Experience"; and Canadian Energy Development Systems International (CEDSI) (1983) prepared a report entitled "Potential for Energy Conservation in the Food and Beverage Industries Through Anaerobic Digestion of Wastes to Methane". In the United States, Pohland and Harper (1985) prepared a paper entitled "Biogas Developments in North America"; Hashimoto (1983) prepared a paper entitled "Commercialization of Anaerobic Digestion Technology in the United States of America"; and John Ashworth et al. (1985) prepared a report entitled "Universe of U.S. Commercial-Scale Anaerobic Digesters: Results of SERI/ARD Data Collection", and another entitled "Problems with Installed Commercial Anaerobic Digestion in the United States: Results of On-Site Visits." In Europe, Nyns and Naveau (1983) presented a paper entitled "Biogas Plants in the European Community and Switzerland. Status-Bottlenecks-Future Prospects"; Anderson and Saw (1984) presented a paper entitled "State of the Art of Anaerobic Digestion for Industrial Applications in the United Kingdom"; and Nyns (1985) prepared a paper entitled "Success or Failure of Biogas Plants in Europe. The Paradox of a Mature Technology."

A summary of the problems identified and conclusions and recommendations made in these papers and reports is presented in Table 8. It is interesting to note that many of the problems occurring with the design, mechanical, and operational and biological aspects of anaerobic digestion systems have been encountered worldwide and that many of the same conclusions and recommendations have been made.

Table 15

ANAEROBIC DIGESTION TECHNOLOGY IN CANADA, THE UNITED STATES AND EUROPE

	Canada	United States	Europe
DESIGN PROBLEMS	- Inadequate mixing - Feedstock handling	- Inadequate heating or heat retention - Feedstock collection, mixing and delivery - Improper equipment sizing	- Feedstock handling - Insufficient mixing and heat transfer
MECHANICAL PROBLEMS	- Gas Metering - Failure of pressure relief valve - Heat exchanger failure - Accumulation of water in biogas line	- Engine generator sets - Feedstock and effluent pumps - Gas cleaning, delivery and storage - Electrical control panels and wiring - Pressure relief valves and protection devices	- Gas metering - Gas leakage - Feedstock pump and feed pipe blockage
OPERATIONAL & BIOLOGICAL PROBLEMS	- Scum formation - Foaming - Feedstock separation - Fixed film media blockage	- Scum build-up - Feedstock separation - Foaming - System start-up - Changes in feedstock composition, temperature and pH - Build-up of inert inorganic solids in digester - Toxicity or pH shocks - Microbial imbalance	- Settlement during storage - Scum formation - Biomass retention - Foreign water entry
CONCLUSIONS	- Agricultural systems are not economically feasible based on energy production alone at current energy prices - Recovery and utilization of protein and phosphorus from digester effluent has not provided the economic incentive to install anaerobic systems - Motivation for installing anaerobic systems will be odour reduction and pollution abatement - Anaerobic systems are an economically and technically feasible alternative to aerobic systems	- Environmental quality control pressures favour the development of anaerobic technology - Biogas energy has been predicted to assume an increasing share of energy budgets although the intensity of associated R & D will remain inextricably linked and vulnerable to economic and political influences - Commercialization of anaerobic digestion technology for converting lignocellulosics such as crop and forest residues is not feasible at this time	- Anaerobic digestion is considered technically feasible, however the technology has suffered from bad publicity from existing facilities, which in most cases were the first systems built by owners or small enterprises - Design and operational information available but widespread, consequently some basic errors have been made over and over again - Many agricultural systems not economically feasible due to high investment costs or low performance - Agricultural systems economically feasible at 400-450 ECU/m^3 digester volume in 1983 - No economies of scale realized at digester volumes greater than 100 m^3 - Digester performance up to 5 times greater for industrial versus agricultural applications - In industrial applications pollution control major objective; energy secondary and often neglected - Anaerobic treatment has become very competitive with aerobic treatment in industrial applications
RECOMMENDATIONS	- Emphasize odour reduction aspect - Develop a simplified test procedure to monitor digestion systems - Develop a comprehensive operator's manual - Determine the influence of animal ration on digestibility and biogas production - Determine the suitability and economic feasibility of recovering nutrients from the anaerobically digested effluent - Improve integration of anaerobic digestion system into farm/plant operation	- Integrate digester into overall farm/plant operations by tailoring digester operations to meet existing operational schedule and local utility constraints - Impress upon anaerobic system operators the importance of regular loading and monitoring schedules - Improve system flexibility to accommodate variations in feedstock composition and availability - Reduce impacts of seasonal fluctuations in ambient conditions and system operations - Perform more work on non-cattle animal manure feedstock - Undertake real-time digester monitoring - Perform effluent product management analysis - Encourage conscientious efforts towards the publication of complete and meaningful accounts of worldwide applications	- Establish national or regional centres to provide digester design, construction and operational information - Promote "do-it-yourself" digesters for economic reasons - Improve integration of digester into farm operations - Investigate the use of energy crops for anaerobic digestion - Develop an operator's manual of practice - Investigate more fully the end uses of digester effluent

Problems with the feedstock collection, mixing and delivery system and inadequate digester mixing and heating were cited as the most common design problems in Canada, the United States and Europe. Mechanical problems were most often related to biogas storage and handling, and feedstock and effluent handling. The most common operational and biological problems encountered were scum formation, foaming and feedstock separation.

Most of the conclusions made indicated that environmental quality control pressures would be the motivation that would favour the development and application of anaerobic digestion technology. It was also universally agreed that anaerobic technology is an economically and technically viable alternative to aerobic technology.

Most of the authors recommended that comprehensive design, construction and operational data should be made available. Other recommendations included the development of an operator's manual, the improvement of the integration of anaerobic digestion systems into existing farm/plant operations and further investigation of the end uses of the anaerobically digested effluent.

5.0 FUTURE PROSPECTS

5.1 Agricultural Sector

The installation of agricultural anaerobic digestion systems in Canada has slowed considerably during the last three years. No new systems have been installed on farms in 1987 and only one system is known to be scheduled for construction in 1988.

The main reasons for the slowdown in system installations are as follows:

a) Energy prices did not continue to rise as anticipated by the National Energy Program predictions. Energy is a much lower priority, and farm businesses feel confident that energy supply and price will be stable in the foreseeable future.

b) Pollution abatement and odour control are still considered important to the larger more progressive farming operations in Canada. However, the cost of installation of anaerobic systems for odour control is still considered to be too high for widespread implementation. Since no regulatory pressure is being applied in most areas of Canada, treatment of manure does not affect minimum acreage requirements for manure disposal, maximum manure application rates, minimum separation distances, etc.

c) Most large producers are confident that anaerobic technology is technically feasible and that it will have a significant impact on odour control and ease manure handling, but cannot justify the cost of the systems for their operations.

5.2 Industrial Sector

The installation of industrial anaerobic digestion systems has been slow but steady during the last three to five years. New systems in Canada are being installed at the rate of one or two per year and will continue at this rate in the foreseeable future.

Most industries are concerned about energy costs and feel that in the long-term they should be looking at methods of reducing energy consumption. However, they see no immediate energy supply and/or price problems in the foreseeable future, and in many cases have seen reductions in energy costs

in the past few years. Until energy prices increase significantly, very little attention will be directed to anaerobic technology as an energy source by these industries. Pollution abatement costs have increased more rapidly than energy costs and more attention is being directed at pollution abatement by the various governments. Many industries will be evaluating their pollution control strategies, especially in Ontario with the Municipal-Industrial Sampling (MISA) program. This will present many opportunities for anaerobic technology to be considered as a low energy consuming technology for industrial waste treatment.

The main reasons for the reluctance in industry to install anaerobic systems are as follows:

a) Many industries, especially in Ontario, have some form of wastewater treatment installed. These systems were installed prior to the "energy crisis" and before interest in anaerobic technology was evident. The capital requirements to install any new technology coupled with the sizeable commitment they have made to their existing treatment plants make it difficult to implement anaerobic technology at this time. As these plants become older and/or the industry expands, opportunities to implement anaerobic technology will exist.

b) Many industries are connected to municipal sewage systems with treatment plants. In many cases, the municipality levies a surcharge on the industry for wastewater treatment. This surcharge is usually correlated to the incremental capital and operating costs of the municipal treatment plant, not the actual cost including capital and financing charges. The surcharge costs for these industries are much lower than the cost of implementing independent wastewater treatment at the plant site. The trend in most municipalities is to bring the surcharge costs up in line with the total wastewater treatment cost at the municipal plant, including capital and financing costs. As these surcharges increase, more industries will install wastewater treatment systems to pretreat wastewater and eliminate the municipal surcharges.

6.0 SUMMARY AND CONCLUSIONS

In 1985-1986, the Canadian Applied Anaerobic Digestion Technology Database and Monitoring Program was developed to monitor full-scale anaerobic digestion systems operating on agricultural and industrial wastes in Canada and to provide a forum for information exchange. The database is stored on the CoSy Computer Conferencing System, developed and operated by the University of Guelph, and is accessible worldwide, with a computer and modem, through DATAPAC or through other similar public switched packet networks.

The long-term anaerobic digestion system monitoring program was established to obtain current operational data and operator/participant comments, questions and suggestions. Once a month, operational monitoring sheets and records are collected from sites where this information is recorded, or samples are collected from sites where no operational records are currently being kept. The summarized operational data and current operating conditions at each site are added to the database on a monthly basis. In 1986, fourteen, full-scale, anaerobic digestion systems were in full operation, and of these, eight were monitored.

A state-of-the-art review of anaerobic digestion technologies was prepared and a discussion of the current trends in the agricultural and industrial sector in Canada, the United States and Europe is presented. Current trends in the agricultural sector indicate that the installation of anaerobic digestion systems for energy production and farm energy savings will not be economically feasible in the foreseeable future. It is anticipated that the motivation for installing anaerobic digestion systems will be odour reduction at site specific locations, unless energy prices increase dramatically. Current trends in the industrial sector indicate that anaerobic digestion technology is being considered as an effective method of wastewater treatment for pollution abatement and a less costly alternative to aerobic treatment.

7.0 RECOMMENDATIONS

It is recommended that in 1987 the digester monitoring program and database activities be continued. Further attempts should be made to obtain design information and operational data from anaerobic digestion facilities that are not currently on the system. An effort should be made to increase the number of participants and an emphasis should be placed on discussion about anaerobic technology and its application in Canada. Suppliers of anaerobic technology should be contacted to obtain company literature and to obtain the suppliers' impressions about the state of the technology.

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APPENDIX A

CANADIAN ANAEROBIC DIGESTION SYSTEM
OPERATIONAL DATA FOR 1986

1986 YEARLY REPORT

System: Agropur Cooperative Agro-Alimentaire

A) General

PARAMETER	MEAN	S.D.*	n**
Average Quantity Pumped (L/d)	350000	78000	4
Average Digester Temperature (°C)	32.3	1.3	4
Hydraulic Retention Time (days)	1.2	0.3	4

B) Digester Influent Data

PARAMETER	MEAN	S.D.*	n**
pH	6.2	0	4
TVS (mg/L)	720	21	4
TSS (mg/L)	790	0	1
COD (mg/L)	2600	120	4
BOD_5 (mg/L)	700	69	3
TKN (mg/g)	90	6.6	4

C) Digester Effluent Data

PARAMETER	MEAN	S.D.*	n**
pH	6.8	0.1	4
TVS (mg/L)	200	83	4
TSS (mg/L)	140	0	1
COD (mg/L)	430	119	4
BOD_5 (mg/L)	310	123	4
TKN (mg/g)	90	1.7	4

* S.D.: Standard Deviation
** n: Number of Samples

D) Biogas Production Data

PARAMETER		MEAN	S.D.*	n**
Flowrate (Biogas)	- m^3 biogas/d	370	59	4
	- m^3/kg VS added.d	1.5	0.4	4
	- m^3/kg COD added.d	0.5	0	1
	- m^3/m^3 digester.d	0.9	0.1	4
	- m^3/kg VS removed.d	2.1	0.3	4
	- m^3/kg COD removed.d	0.6	0	1
Flowrate (Methane)	- m^3 methane/d	261	40	4
	- m^3/kg VS added.d	1.1	0.3	4
	- m^3/kg COD added.d	0.4	0	1
	- m^3/m^3 digester.d	0.6	0.1	4
	- m^3/kg VS removed.d	1.5	0.2	4
	- m^3/kg COD removed.d	0.4	0	1
Biogas Quality	- $\%CH_4$	71	1.1	4

E) Loading Rates

PARAMETER	MEAN	S.D.*	n**
Kg TVS/d	250	57	4
Kg TVS/m^3 digester.d	0.6	0.1	4
Kg COD/d	910	199	4
Kg COD/m^3 digester.d	2.2	0.5	4

* S.D.: Standard Deviation
** n: Number of Samples

1986 YEARLY REPORT

System: Buteau and Tremblay Farm

A) General

PARAMETER	MEAN	S.D.*	n**
Average Quantity Pumped (L/d)	7900	2200	12
Average Digester Temperature (°C)	34.3	1.3	12
Hydraulic Retention Time (days)	7.0	2.5	12

B) Digester Influent Data

PARAMETER	MEAN	S.D.*	n**
pH	7.6	0.2	10
TS (mg/L)	25500	9860	10
TVS (mg/L)	17600	7800	10
COD (mg/L)	40900	9700	10

C) Digester Effluent Data

PARAMETER	MEAN	S.D.*	n**
pH	8.0	0.1	10
TS (mg/L)	18100	9250	10
TVS (mg/L)	12000	7560	10
COD (mg/L)	25600	8310	10

* S.D.: Standard Deviation
** n: Number of Samples

D) Biogas Production Data

PARAMETER		MEAN	S.D.*	n**
Flowrate (Biogas)	- m^3 biogas/d	40	8.7	12
	- m^3/kg VS added.d	0.4	0.2	10
	- m^3/kg COD added.d	0.1	0.04	10
	- m^3/m^3 digester.d	0.7	0.3	12
	- m^3/kg VS removed.d	1.7	1.7	10
	- m^3/kg COD removed.d	0.4	0.1	10
Flowrate (Methane)	- m^3 methane/d	28	6.3	12
	- m^3/kg VS added.d	0.3	0.1	10
	- m^3/kg COD added.d	0.1	0.02	10
	- m^3/m^3 digester.d	0.6	0.22	12
	- m^3/kg VS removed.d	1.2	1.2	10
	- m^3/kg COD removed.d	0.2	0.1	10
Biogas Quality	- $\%CH_4$	70	2.6	12

E) Engine Co-generation System Data

PARAMETER	MEAN	S.D.*	n**
Hours of Operation (hr/d)	2.1	2.0	6
Average kW-hr Production (kW-hr/d)	0.3	0.3	6

F) Loading Rates

PARAMETER	MEAN	S.D.*	n**
Kg TVS/d	125	44	10
Kg TVS/m^3 digester.d	2.5	0.9	10
Kg COD/d	300	79	10
Kg COD/m^3 digester.d	6.1	1.6	10

* S.D.: Standard Deviation
** n: Number of Samples

1986 YEARLY REPORT

System: Gasser Farms Ltd.

A) General

PARAMETER	MEAN	S.D.*	n**
Average Quantity Pumped (L/d)	35600	5430	5
Average Digester Temperature (°C)	32.2	2.5	5
Hydraulic Retention Time (days)	17.2	2.8	5

B) Digester Influent Data

PARAMETER	MEAN	S.D.*	n**
pH	7.54	0.4	5
TS (mg/L)	97400	16280	5
TVS (mg/L)	76700	13400	5
COD (mg/L)	87100	0	1
TKN (mg/L)	3800	760	5

C) Digester Effluent Data

PARAMETER	MEAN	S.D.*	n**
pH	8.1	0.2	4
TS (mg/L)	71000	0	1
TVS (mg/L)	54000	0	1
COD (mg/L)	48000	0	1
TKN (mg/L)	4000	0	1

* S.D.: Standard Deviation
** n: Number of Samples

D) Biogas Production Data

PARAMETER		MEAN	S.D.*	n**
Flowrate (Biogas)	- m^3 biogas/d	398	117	5
	- m^3/kg VS added.d	0.1	0.01	5
	- m^3/m^3 digester.d	0.7	0.2	5
	- m^3/kg VS removed.d	0.4	0	1
Flowrate (Methane)	- m^3 methane/d	239	71	5
	- m^3/kg VS added.d	0.1	0.01	5
	- m^3/m^3 digester.d	0.4	0.1	5
	- m^3/kg VS removed.d	0.3	0	1
Biogas Quality	- $\%CH_4$	60	0.2	5

E) Engine Co-generation System Data

PARAMETER	MEAN	S.D.*	n**
Hours of Operation (hr/d)	15	4.2	5
Average kW-hr Production (kW-hr/d)	457	127.8	5

F) Loading Rates

PARAMETER	MEAN	S.D.*	n**
Kg TVS/d	2751	673	5
Kg TVS/m^3 digester.d	4.6	1.1	5
Kg COD/d	3400	0	1
Kg COD/m^3 digester.d	5.7	0	1

* S.D.: Standard Deviation
** n: Number of Samples

1986 YEARLY REPORT

System: Kemptville College

A) General

PARAMETER	MEAN	S.D.*	n**
Average Quantity Pumped (L/d)	612	365	6
Average Digester Temperature (°C)	51.7	7.5	6
Hydraulic Retention Time (days)	76.8	64.8	6

B) Digester Influent Data

PARAMETER	MEAN	S.D.*	n**
TS (mg/L)	48400	11940	6
TVS (mg/L)	40300	10120	6
COD (mg/L)	50400	9830	3
TKN (mg/L)	3300	310	3

C) Digester Effluent Data

PARAMETER	MEAN	S.D.*	n**
pH	8.3	0.2	6
TS (mg/L)	29000	6020	6
TVS (mg/L)	22200	4960	6
COD (mg/L)	23800	5180	3
TKN (mg/L)	2400	490	3

* S.D.: Standard Deviation
** n: Number of Samples

D) Biogas Production Data

PARAMETER		MEAN	S.D.*	n**
Flowrate (Biogas)	- m^3 biogas/d	28	12.6	3
	- m^3/kg VS added.d	3.3	1.8	3
	- m^3/m^3 digester.d	1.0	0.5	3
	- m^3/kg VS removed.d	6.5	2.1	2

E) Loading Rates

PARAMETER	MEAN	S.D.*	n**
Kg TVS/d	27	18	6
Kg TVS/m^3 digester.d	1.0	0.7	6
Kg COD/d	46	13	3
Kg COD/m^3 digester.d	1.7	0.5	3

* S.D.: Standard Deviation
** n: Number of Samples

1986 YEARLY REPORT

System: Millbank Cheese and Butter Ltd.

A) General

PARAMETER	MEAN	S.D.*	n**
Average Quantity Pumped (L/d)	14400	2940	11
Average Digester Temperature (°C)	34.1	1.1	11
Hydraulic Retention Time (days)	79.9	18.5	11

B) Digester Influent Data

PARAMETER	MEAN	S.D.*	n**
pH	5.2	0.7	10
TS (mg/L)	57500	4210	11
TVS (mg/L)	39600	3450	2
COD (mg/L)	66200	8010	11
BOD_5 (mg/L)	35000	0	1
TKN (mg/L)	1300	0	1
P (mg/L)	530	0	1
K (mg/L)	1500	0	1

C) Digester Effluent Data

PARAMETER	MEAN	S.D.*	n**
pH	6.9	0.2	11
TS (mg/L)	15400	1880	8
TVS (mg/L)	10100	1890	2
COD (mg/L)	13300	3510	11
BOD_5 (mg/L)	4400	1630	7
TKN (mg/L)	1700	0	1
P (mg/L)	720	0	1

* S.D.: Standard Deviation
** n: Number of Samples

D) Biogas Production Data

PARAMETER		MEAN	S.D.*	n**
Flowrate (Biogas)	- m^3 biogas/d	512	139	10
	- m^3/kg COD added.d	0.6	0.2	10
	- m^3/m^3 digester.d	0.5	0.1	10
	- m^3/kg COD removed.d	0.8	0.3	10
Flowrate (Methane)	- m^3 methane/d	238	65	8
	- m^3/kg COD added.d	0.3	0.1	8
	- m^3/m^3 digester.d	0.2	0.1	8
	- m^3/kg COD removed.d	0.4	0.1	8
Biogas Quality	- $\%CH_4$	46	4.5	8
	- $\%CO_2$	39	2.8	8

E) Loading Rates

PARAMETER	MEAN	S.D.*	n**
Kg TVS/d	537	49	2
Kg TVS/m^3 digester.d	0.5	0.05	2
Kg COD/d	965	253	11
Kg COD/m^3 digester.d	0.9	0.2	11

* S.D.: Standard Deviation
** n: Number of Samples

1986 YEARLY REPORT

System: Olds College

A) General

PARAMETER	MEAN	S.D.*	n**
Average Quantity Pumped (L/d)	13900	4081	9
Average Digester Temperature (°C)	35.2	0.3	9
Hydraulic Retention Time (days)	31.3	12	9

B) Digester Influent Data

PARAMETER	MEAN	S.D.*	n**
pH	6.9	0.1	3
TS (mg/L)	42100	3886	3
TVS (mg/L)	31400	4295	3
COD (mg/L)	42600	1974	3
TKN (mg/g)	2.7	0.2	3
P (mg/L)	770	116	3
K (mg/L)	920	57	3

C) Digester Effluent Data

PARAMETER	MEAN	S.D.*	n**
pH	7.7	0	3
TS (mg/L)	25600	3374	3
TVS (mg/L)	16700	3015	3
COD (mg/L)	24500	3310	3
TKN (mg/g)	2.6	0.4	3
P (mg/L)	630	121	3
K (mg/L)	910	67	3

* S.D.: Standard Deviation
** n: Number of Samples

D) Biogas Production Data

PARAMETER		MEAN	S.D.*	n**
Flowrate (Biogas)	- m^3 biogas/d	135	17	5
	- m^3/m^3 digester.d	0.35	0.04	5
Flowrate (Methane)	- m^3 methane/d	82	11	5
	- m^3/m^3 digester.d	0.2	0.03	5
Biogas Quality	- $\%CH_4$	61	1.2	5
	- $\%CO_2$	37	1.1	5

E) Loading Rates

PARAMETER	MEAN	S.D.*	n**
Kg TVS/d	481	59	3
Kg TVS/m^3 digester.d	1.2	0.2	3
Kg COD/d	665	49	3
Kg COD/m^3 digester.d	1.7	0.1	3

* S.D.: Standard Deviation
** n: Number of Samples

1986 YEARLY REPORT

System: Pittens Farms Ltd.

A) General

PARAMETER	MEAN	S.D.*	n**
Average Quantity Pumped (L/d)	10000	0	2
Average Digester Temperature (°C)	35.9	0.8	2
Hydraulic Retention Time (days)	27.5	0	2

B) Digester Influent Data

PARAMETER	MEAN	S.D.*	n**
pH	7.1	0	1
TS (mg/L)	105100	17850	2
TVS (mg/L)	75100	16900	2
COD (mg/L)	109100	3622	2
TKN (mg/g)	5.3	0.8	2
NH_3-N (mg/g)	2.7	0.1	2

C) Digester Effluent Data

PARAMETER	MEAN	S.D.*	n**
pH	7.8	0	2
TS (mg/L)	65800	3200	2
TVS (mg/L)	43800	4200	2
COD (mg/L)	61400	3200	2
TKN (mg/L)	4.6	0.6	2
NH_3-N (mg/g)	2.8	0.1	2

* S.D.: Standard Deviation
** n: Number of Samples

D) Biogas Production Data

PARAMETER		MEAN	S.D.*	n**
Flowrate (Biogas)	- m^3 biogas/d	144	7.5	2
	- m^3/kg VS added.d	0.2	0.1	2
	- m^3/m^3 digester.d	0.5	0.03	2
	- m^3/kg VS removed.d	0.6	0.3	2
Flowrate (Methane)	- m^3 methane/d	82	7	2
	- m^3/kg VS added.d	0.1	0.03	2
	- m^3/m^3 digester.d	0.3	0.03	2
	- m^3/kg VS removed.d	0.3	0.2	2
Biogas Quality	- $\%CH_4$	57	1.7	2
	- $\%CO_2$	33	1.9	2

E) Engine Co-generation System Data

PARAMETER	MEAN	S.D.*	n**
Hours of Operation (hr/d)	6.5	0.5	2
Average kW-hr Production (kW-hr/d)	260	20	2
Average Specific Fuel Consumption			

F) Loading Rates

PARAMETER	MEAN	S.D.*	n**
Kg TVS/d	751	169	2
Kg TVS/m^3 digester.d	2.7	0.6	2
Kg COD/d	1090	36	2
Kg COD/m^3 digester.d	4.0	0.1	2

* S.D.: Standard Deviation
** n: Number of Samples

1986 YEARLY REPORT

System: Selves Farms Ltd.

A) General

PARAMETER	MEAN	S.D.*	n**
Average Quantity Pumped (L/d)	16500	1900	12
Average Digester Temperature (°C)	35.1	1.2	12
Hydraulic Retention Time (days)	13.9	1.5	12

B) Digester Influent Data

PARAMETER	MEAN	S.D.*	n**
pH	7.2	0.2	12
TS (mg/L)	48500	13220	12
TVS (mg/L)	33400	10370	12
COD (mg/L)	69800	14250	12
TKN (mg/L)	6500	920	11
P (mg/L)	1700	430	11
K (mg/L)	2200	550	12

C) Digester Effluent Data

PARAMETER	MEAN	S.D.*	n**
pH	8.2	0.3	12
TS (mg/L)	32500	10250	12
TVS (mg/L)	20400	9750	12
COD (mg/L)	31700	7850	12
TKN (mg/L)	6700	860	6
P (mg/L)	1500	370	7
K (mg/L)	2300	600	7

* S.D.: Standard Deviation
** n: Number of Samples

D) Biogas Production Data

PARAMETER		MEAN	S.D.*	n**
Flowrate (Biogas)	- m^3 biogas/d	278	54	10
	- m^3/kg VS added.d	0.5	0.2	10
	- m^3/kg COD added.d	0.3	0.1	10
	- m^3/m^3 digester.d	1.2	0.2	10
	- m^3/kg VS removed.d	1.01	0.5	7
	- m^3/kg COD removed.d	0.5	0.2	10
Flowrate (Methane)	- m^3 methane/d	178	35	10
	- m^3/kg VS added.d	0.4	0.2	10
	- m^3/kg COD added.d	0.2	0.1	10
	- m^3/m^3 digester.d	0.8	0.2	10
	- m^3/kg VS removed.d	0.6	0.2	7
	- m^3/kg COD removed.d	0.3	0.1	10
Biogas Quality	- $\%CH_4$	64	1.8	11
	- $\%CO_2$	28	2.7	11

E) Engine Co-generation System Data

PARAMETER	MEAN	S.D.*	n**
Hours of Operation (hr/d)	24	0	7
Average kW-hr Production (kW-hr/d)	222	113.6	10
Average Specific Fuel Consumption (m^3 biogas/kW-hr)	1.5	0.7	9

* S.D.: Standard Deviation
** n: Number of Samples